Electrical Engineering

To Measure—MOISTURE CONTENT
ELECTRICALLY

MOISTURE is an elusive agent—all-pervading in nature and difficult to detect, difficult to eliminate or control. And when there's moisture in supposedly dry annealing gases, high-carbon steel decarburizes and becomes unsatisfactory for many uses. Razor blades made from it have poor edges; automobile and airplane gears do not hold up in service.

To help eliminate this handicap, G-E engineers were asked to devise an instrument which would improve annealing and heat-treating operations by determining the moisture content of gases. As "Headquarters for Electrical Measurement," the G-E laboratories had already solved other tough problems for industry—had made instruments to measure lightning surges and the trickle of electrons in a vacuum, instruments to measure color exactly and instruments to unscramble sound waves; and now they set to work on measuring moisture.

The result was a portable potentiometer which measures the dew point, or temperature at which moisture will condense from a sample of gas. (It's described in Publication GEA-2630, which is yours for the asking.) The moisture condenses on a thin, metallic mirror connected to a thermocouple and then to an indicating instrument. An operator regulates the flow of the cooling medium against the back of the mirror until the exact condensation point, or dew point, is reached and temperature readings can be made. Thus, another measurement problem was solved.

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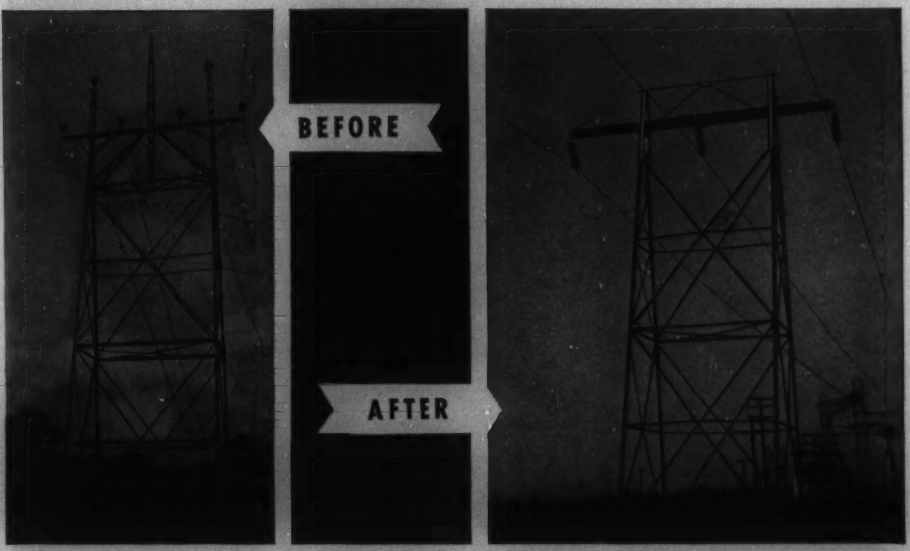

UNDER favorable conditions, the life of galvanized steel is practically indefinite, but electrical requirements often change. A good line may be headed for obsolescence simply because continued, economical operation may dictate stepped-up electrical capacity and voltage. The problem is not infrequent in our experience.

A typical example was an 85-mile transmission line in the south. This old pin type two-circuit 66 KV line could no longer meet requirements. The change required was to a single-circuit 110 KV line.

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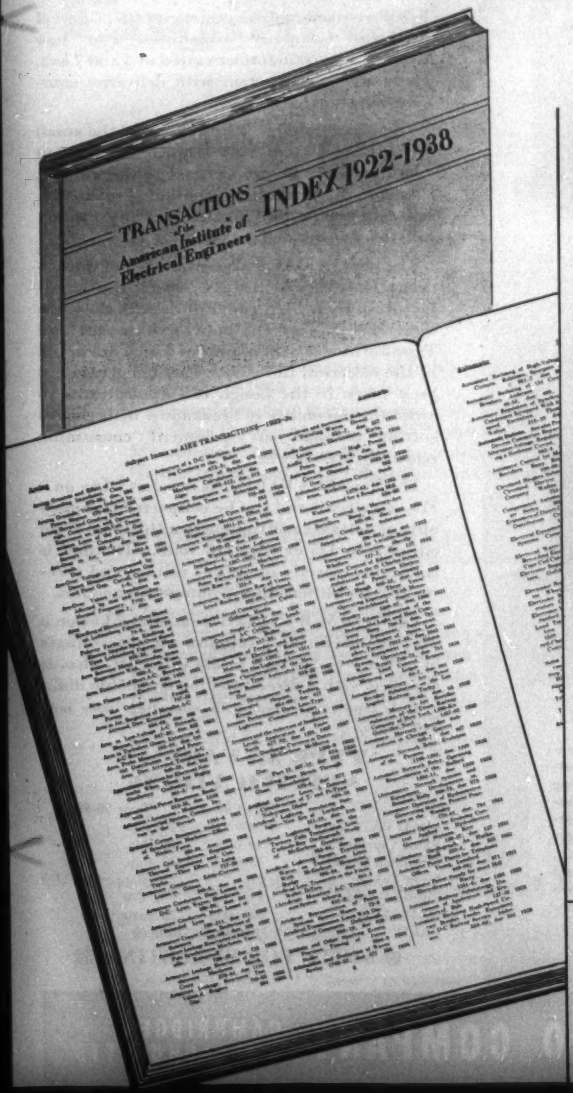
UNITED STATES STEEL

NEW INDEX

of the AIEE TRANSACTIONS from 1922 to 1938 Inclusive



A new cumulative Index, covering the papers and discussions published in the AIEE TRANSACTIONS from January 1, 1922 to December 31, 1938, is now available for distribution. This new compilation constitutes the fourth in a series of published volumes of indexes to the technical papers and related discussions that have been published by the Institute since 1884.

No effort has been spared in making this new volume of maximum serviceability to its users. It contains generous multiple entries. It has been composed in much larger type and with more generous spacing than is commonly used for index purposes. It has been arranged for convenience in use, and is printed on special, heavy strong paper of the "easy reading" tint that has proved so successful in ELECTRICAL ENGINEERING. Sturdily bound in green cloth to match the TRANSACTIONS—and for durability stamped in genuine gold leaf—this Index volume contains 160 TRANSACTIONS-size pages, 8⅝ x 11¼ inches.

For convenience, the volume is divided into two sections:

1. Subject Index. Arranged alphabetically, the more than 9,000 entries in this section provide multiple references to every technical paper and related discussion published during the 17 years covered by the Index. The title of each technical paper has been entered under every significant word in the title and has been given certain additional listings such as the subject name of the technical committee responsible for the review and recommendation of the paper. Thus, a searcher may effectively approach a desired reference through any of several key words associated with the subject matter of the item sought.

2. Author Index. Every author or co-author of a technical paper or discussion published in the TRANSACTIONS during the 17 years covered by the Index is listed alphabetically in this section. The 11,000-odd entries give direct page reference to each paper and each published discussion.

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Electrical Engineering

Registered U. S. Patent Office

for August 1939—

The Cover: Permanently evacuated and air-cooled 100-kw 600-volt glass-tube rectifier unit. Photo Courtesy Allis-Chalmers

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VOLUME 58 NUMBER 8

Published Monthly by the

American Institute of Electrical Engineers

(Founded 1884)

F. MALCOLM FARMER, President H. H. HENLINE, National Secretary

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Entered as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918. ¶ Publication Office: 20th & Northampton Streets, Easton, Pa. Editorial and Advertising Offices at the headquarters of the Institute, 33 West 39th Street, New York

¶ Statements and opinions given in articles and papers appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility.

¶ Correspondence is invited on all controversial matters.

High Lights

Overvoltages. One session of the 1939 AIEE winter convention was devoted to the subject of the high transient voltages that may appear on power systems as the result of switching operations, lightning, and faults. In one paper the factors that determine the maximum voltages which may be obtained on a system following the occurrence of faults are reviewed and analyzed, and results of calculations and tests on a miniature system are presented (*Transactions pages 377–85*). Another miniature system was used for tests to determine recovery voltages with special reference to interruption of faults by protector tubes (*Transactions pages 405–13*). Several theories for the production of overvoltages are reviewed in a paper that reports studies of transients on a network calculator of a range of grounding conditions (*Transactions pages 386–97*). The effect of resistance on the closing and opening transients of inductive and capacitive a-c circuits is demonstrated graphically in a paper that also gives the mathematical basis for the curves (*Transactions pages 397–404*). Extremely high voltages theoretically may build up under certain circuit conditions from successive momentary clearing and re-establishment of current flow during switching operations, although tests show that the voltage actually realized is always less than the theoretical maximum (*Transactions pages 371–6*).

Summer Convention. A full report of the recent AIEE combined summer and Pacific Coast convention, supplementing the initial report in the July issue, includes, in addition to the main account of the convention (*pages 350–2*), a digest of discussion at the annual conference of officers, delegates, and members (*pages 352–4*), a summary of actions taken at the meeting of the Institute's board of directors (*page 355*), and a report of the board of directors' action on the proposed AIEE Model Law on the registration of engineers (*pages 354–5*).

Air Circuit Breakers. Use of a new form of deionizing arc interrupter for enclosed air circuit breakers for low voltages aids in reducing arc flame and gases, and together with other improvements leads to increased current-carrying capacity for a given size of breaker (*Transactions pages 414–20*). An air circuit breaker of the deionizing type for moderate-voltage switchgear has been tested with currents in excess of 37,000 amperes at 15 kv (*Transactions pages 421–6*).

American Engineering Council. Among items appearing in the current AEC *Bulletin* are: announcement of the new director of Federal public works; compilation of bills affecting patent procedure now under consideration by Congress; summary of some of the findings of the Federal Power Commission's study of utility companies in 1937 (*pages 357–8*).

High-Voltage Circuit Breakers. The standard circuit-breaker interrupting time of 8 cycles on a 60-cycle basis has been reduced to 5 cycles in the voltage classes from 138 to 230 kv by a new multiple-unit interrupter assembly that was evolved from a design used at lower voltages (*Transactions pages 427–34*).

Branch Prize Paper. A method of determining the efficiencies of fractional-horsepower motors from the heat produced by eddy currents is described in the current AIEE national Branch prize paper. The method obviates the principal disadvantages of brake methods and is simple enough to be easily applicable in industry (*pages 339–40*).

AIEE Lamme Medal. Eleventh recipient of the Lamme Medal, awarded annually to a member of the Institute for "meritorious achievement in the development of electrical apparatus or machinery," is Marion A. Savage (A'21). Presentation was made during the Institute's recent summer convention at San Francisco, Calif. (*pages 347–9*).

Responsibilities. If our conduct is to be more than a perfunctory performance of ritual, we must first know what we are after, says Retiring-President John C. Parker in discussing the responsibilities of the officers and individual members of the AIEE in his summer-convention address (*pages 330–2*).

Fibrous-Glass Insulation. Because of its advantages over organic materials, fibrous glass is finding increasing applications for insulation in electrical machines. Tests on unimpregnated samples demonstrate its superior qualities at high gas pressures and temperatures (*pages 341–5*).

More Use for the Decibel. The decibel scale and the geometrical progression on which it is based can be applied to the measurement of heat, light, electricity as well as to that of sound, says a communications engineer who foresees increasingly wide use for this unit (*pages 328–9*).

Modern Railway Signals. The track circuit, foundation of nearly all modern signaling, is analyzed and its development traced, in an article which also surveys background and present use of automatic train control and cab signals, centralized traffic control, and route interlocking (*pages 333–8*).

District Meetings. Plans are progressing for meetings to be held by the AIEE Great Lakes District at Minneapolis, Minn., September 27–29 (*pages 356–7*), and the Middle Eastern District at Scranton, Pa., October 11–13 (*page 356*).

District 4 Executive Committee. Delegates from the AIEE Southern District at a luncheon meeting during the recent summer convention discussed prospects for the 1941 summer convention (*pages 355–6*).

Traveling Waves. Separation of the components of traveling waves on power transmission lines may be accomplished by means of a special bridge circuit (*pages 345–6*).

District Paper Prizes. Prize awards for 1938 papers have been announced by three AIEE Districts (*pages 355–6*).

Coming Soon: Among special articles and technical papers now undergoing preparation for early publication are: an article on "Human Relationships," by A. S. Bennion, containing the essential substance of an address delivered at the general session of the recent AIEE combined summer and Pacific Coast convention; an article pointing out the dangers of the misconception that engineering methods can be applied as effectively to social as to technological problems, by R. W. King (M'35); an article reviewing the various methods of applying geophysics to the location of oil deposits, by Daniel Silverman (A'33); a paper on the rating of general-purpose induction motors by P. L. Alger (F'30) and T. C. Johnson (A'35); a paper on duty cycles and motor rating by L. E. Hildebrand (M'21); papers on the measurement of temperature in induction motors by E. R. Summers (A'38) and C. P. Potter (F'29); a paper discussing the temperature aging characteristics of class *A* insulation by J. J. Smith (A'19) and J. A. Scott (M'34); and a paper on temperature limits set by oil and cellulose insulation by C. F. Hill (M'29).

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Number of copies this issue 20,900

A Message From the President

To Members of the Institute:

IN RESPONSE to President Parker's most gracious introduction of the new President at the AIEE annual meeting in San Francisco after the announcement of the result of the election of new officers, I stated that I found myself at a loss for words which would adequately express my appreciation of the honor which has been bestowed upon me. The purpose of this "open letter," in addition to extending greetings to the membership, is to repeat that statement here for the benefit of those members of the Institute who were not present on that occasion, to thank all of you for your approval of the selection of the nominating committee, and to express the hope that your confidence will prove justified.

The principal duty which is officially assigned to the president is "general supervision of the affairs of the Institute under the direction of the board of directors." That is now very largely a nominal duty. With the conscientious boards of directors and the able national secretary which the Institute is fortunate in having, its affairs require very little supervision by the president. I expect to devote my attention principally to those matters which will help to maintain the best traditions of the Institute and which will assist in increasing its prestige as the professional body in the electrical branch of the engineering field.

It is quite probable that my conduct of the affairs of the Institute will not always meet with the full approval of all of our nearly 17,000 members. You will recall the time-honored story of the Scotchman living on the outskirts of the town who, upon the announcement of the street-railway company that fares would be reduced from five cents each to six rides for 25 cents, complained of the change on the ground that he had to walk to town six times instead of five to save a shilling. However, it should be remembered that it is not what the president does or says that is important. It is the actions of the board of directors that are important. The members of the board are selected by you and endeavor to carry out your wishes insofar as possible with due consideration to the best interests of the greatest number. But the board cannot know the desires of the membership unless they are made known. The members are therefore urged to keep in mind that this is a co-operative, voluntary organization in which each member has not only a right but a duty to submit directly to headquarters or through his District vice-president suggestions for increasing the value and influence of the Institute, and to express his opinion on the conduct of the affairs of the Institute whether such opinion is commendatory or otherwise.

Thanks to the able and efficient previous administrations, the material affairs of the Institute are in excellent shape. We are operating well within our income, our membership is steadily growing, and activities in the Sections and the Branches are steadily increasing. We have, however, at least two general problems confronting us which should be kept in mind as ones that will probably require more and more attention as time goes on. One is the meeting of the growing demands on the Institute's financial resources incident to the increasing membership and to the expanding scope of the electrical-engineering field. The other is the less material but perhaps more important one of maintaining electrical engineering on a professionally high plane. The stresses resulting from the social and economic changes of the past few years should not be allowed to develop strains beyond the elastic limit—beyond the point where we cease to conform to the tenets of a true profession. However, these and other problems that will confront us will be met with credit to the Institute and the profession if each of us will take as prideful and active an interest in its affairs as his opportunities will permit.

F. Malcolm Farmer

How Many Decibels?

H. P. LAWTHER
ASSOCIATE AIEE

Although the decibel and its relation to the theory of geometrical progression are familiar to communications engineers and engineering educators, many other engineers have not had occasion to analyze the implications of this comparatively new unit. To them, this article presents a definition in understandable terms.

IN 1925 the International Advisory Committee on Long Distance Telephony gave official recognition to the decibel as a unit for use in telephony. For a number of years previous in this and allied fields necessity had been mothering several varieties of a unit of the same fundamental character, and the action of the committee was a welcome and helpful step toward uniformity. The sciences of telephony, acoustics, and radio have experienced such rapid development and have attracted such widespread interest in recent years that by now their more common terminology has reached the sidewalk level. Many engineers, however, have not had occasion to work in these fields, and some may have wondered just what sort of thing the decibel is. Recourse to the dictionary has not been satisfactory, for there one found some such barren definition as "the logarithmic unit of power increment," or "the usual unit for measuring the loudness of sound." Inquiry of some worker applying this unit in his daily tasks usually has proved equally futile. The difficulty has been that the concept upon which the decibel is based is as fundamental as human experience itself, and fundamental things in general cannot be described in tersely worded definitions.

For a moment let us turn back our imaginations to the early days of man's existence, when he was just beginning to learn to count and reckon. Imagine one shepherd of this age gathering his flock into the fold at nightfall and checking them in by driving them one at a time through a narrow gateway—transferring a pebble from one basket to another as each sheep passed through the opening. His experience at the moment would naturally suggest a pattern such as that shown on figure 1—where the group of sheep within the fold or the group of pebbles in one of the baskets would increase by successive increments of one. The succession of quantities thus suggested to him is, of course, the set of real integral numbers. This is the most fundamental of all arithmetical progressions and is characterized by the constant difference of unity between successive members.

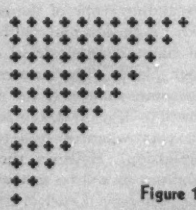


Figure 1

At the same time a neighboring shepherd might have completed checking in his flock for the evening and been looking toward the morrow in a contemplative frame of mind. He well might have been thinking of his ewe that had borne twin ewe lambs last spring, of the twin lambs which each of these in turn would bring forth next season, and so on, and thus of the tremendous herd he would have in a remarkably short space of time. This man's experience at the moment would naturally suggest a pattern such as that indicated in figure 2—a geometrical progression of integral numbers characterized by a constant ratio of two between successive members.

The patterns of figures 1 and 2 are equally fundamental to human experience, and the man who is led to the one

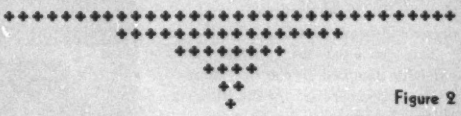


Figure 2

is not necessarily more deeply thoughtful or more mathematically inclined than the man who is led to the other. The arithmetical progression was tremendously favored, however, by the invention of very convenient and workable symbols whereby counting and reckoning in this scale could be mastered by entire populations. The arithmetical progression, therefore, is the basis for the form of counting and reckoning which we today and our ancestors for centuries past learned so early in our lives that our very thinking machinery has been built up around it. For most of us formal introduction to the geometrical progression occurred when we reached the chapter on logarithms in our high-school algebras. We learned there that certain reckonings could be accomplished in this scale with extraordinary facility, but it was too late to do anything except learn to use the conversion tables for interpreting it in terms already familiar. Logarithms are only 300 years old, and while they have been of inestimable value, their use has been confined to a comparatively small group, comprising such specialists as astronomers, navigators, engineers, statisticians, and computers. For the great bulk of the population, logarithms and the employment of the geometrical scale have meant nothing at all.

While there has been no widespread acceptance of a system of counting or reckoning based upon a geometrical scale, it has been inevitable that a thing so fundamental must have thrust itself to the fore in many ways. The

Based upon a talk given at several AIEE Section meetings in the South West District in April 1939.

H. P. LAWTHER is transmission engineer, Southwestern Bell Telephone Company, St. Louis, Mo.

human sense of hearing is such that the musical octave has been necessary, and the octave is simply a unit step in a geometrical progression of frequencies based on a ratio of two. The succession of the cross-section areas for the Brown and Sharpe wire gauges follows with startling accuracy a geometrical progression with a base ratio of approximately 1.25. The obvious properties of an electrically long uniform transmission line forced the geometrical scale on telephone workers early in that science. The "standard mile," the "800 cycle mile," the "1000 cycle mile," and the "transmission unit" represented successively the birth, babyhood, childhood, and adolescent stage of the decibel itself. The several series of "preferred numbers" advocated by those interested in standardization are practical approximations to geometrical progressions that experience has taught to be desirable for governing the stock sizes of such things as nuts, bolts, screws, pins, or shafting. The use of logarithmic plotting paper and of the slide rule are more obvious examples.

From the point of view of this discussion, then, the decibel is to be defined as a number of value $10^{0.1}$ (approximately 1.26) used as the base ratio for a geometrical progression. The value of exactly $10^{0.1}$ has been chosen for two good reasons: First, it yields a unit of convenient size; and, second, it ties in directly with the tables of common logarithms which are universally available, and so facilitates conversions between this and the arithmetical scale. Both this number and the geometrical progression it governs are totally abstract magnitudes, equally applicable to the quantities encountered in sound, heat, light, electricity, animal husbandry, or any other field of experience where they may prove convenient and useful.

The geometrical scale differs fundamentally from the arithmetical in that it does not contain a natural zero reference point. It extends to infinitely large magnitudes in the upward direction, but it can never reach zero or attain a negative value. This peculiarity offers no drawback where the quantity under consideration is essentially positive in character and where experience suggests some logical and readily remembered reference value.

The communications engineer refers his "measured transmission loss" to his ideal of an electrically long, uniform, distortionless transmission line. A measured or computed result of 10 decibels, say, for a piece of apparatus or for a circuit would mean that the power received at the distant end of the transmission line would be reduced to $^1/_{10}$ of its value by the insertion of this item into the otherwise uniform line. In laying out his circuits the communications engineer designates one milliwatt as his reference for the power level (that is, peak value measured with a specified form of instrument) of the voice currents on the circuits. A level of +10 decibels or a level of −20 decibels would indicate 10 milliwatts or $^1/_{100}$ of a milliwatt, respectively. For measuring the noisiness of the extraneous currents that get onto any telephone circuit he elects a much smaller reference value, and designates 10^{-12} watts at 1,000 cycles for this purpose. A noise level of 30 decibels on a circuit would mean that the noise currents present as translated to the ear of an average telephone listener would produce a sound as loud as 1,000 times 10^{-12} watts of 1,000-cycle current would produce under the same circumstances.

When the same engineer is interested in the noisiness of a room in which a telephone instrument is located he employs the reference standard adopted by the acoustical people, namely, 10^{-16} watts per square centimeter for a 1,000-cycle free progressive wave in air. A room-noise level of 50 decibels at a given point would mean that an average human ear placed there would hear a sound of loudness equal to that of a 1,000-cycle free progressive wave in air of intensity equal to 10^5 times 10^{-16} watts per square centimeter. While applications have not as yet been made in such fields as temperature and illumination measurement, the decibel scale suggests itself as quite appropriate for these, and the writer has no doubt that the near future will find increasing use for it.

The fact that today large numbers of the population are employing the decibel unit in their daily activities and thinking—meaning that for the first time in man's history a geometrical scale of reckoning is getting down to the grass roots—offers an intriguing suggestion. The one mental computing wizard that this writer has had the opportunity to observe employed a pencil and paper and performed a perfunctory operation resembling addition when asked to multiply two large numbers together. Except for his extraordinary ability in this one particular, this individual appeared to be of very ordinary intellectual capacity. The presumption persists with the writer, therefore, that this man was exceptional only in that by accident he escaped the stupefying effects of conventional childhood educational routine, and was able to invent for himself a computing scale based on a geometrical progression—for in this scale multiplication is accomplished by operations similar to the simple ones that result in addition with the arithmetical scale. The suggestion that with future generations wizardry in computation may be the rule rather than the exception is left for the reader's fancy.

Decibels

Watch the meter as it tells
Decibels!
Profound confusion while it spells
Decibels!
Frequency and decibels are one.
A DB would not in decency
Be seen without a frequency.
As hearing is subjective
And a DB is objective
Loudness is a science just begun.

We are muddled up with DBs
Until we get the DTs.
From their sly implications
Often spoofy,
They give indications
Often goofy.
But the engineer will win
And the DB will give in,
And noise will be defined throughout the world,
By the straining and the gaining
of the bells,
Decibels!

T. M. Blakeslee (A'29) Los Angeles Section, AIEE)

Responsibilities in the AIEE

JOHN C. PARKER
PRESIDENT AIEE, 1938-39

For the Institute and its membership, Retiring-President Parker recommends "individual responsibility, individual work, and an organization developed along representative lines"

PART of the ritual of the AIEE annual meeting seems by tradition to be an address by the president of the Institute. Please note that it is an *address* that is called for and not a *paper*, the presumption being, I suppose, that the president of the Institute should not or could not present a technical paper. In the present instance this presumption is sound on both counts.

I do not know why commencement orations and presidential addresses are given. It may be that there is an illuminating parallel provided by that most sagacious of ancient animals, the African elephant. I understand that in crossing a crocodile-infested stream the old bulls go first and so muddy the waters that the younger members of the herd have protection through the creation of the screen churned up from the river bottom.

Then again it may be that an outgoing officer is tossed an opportunity through this device to make himself believe what all his auditors know to be sheer fantasy, namely, that he still has a spark of life left in him. In any case, if valedictories must be pronounced, I would much sooner make them than listen to them.

During the administrative year now closing I have had occasion—or opportunity if you will—to make quite a series of addresses at District, Section, and Branch meetings. This verbal outpouring has seriously mitigated the otherwise very great happiness that has come from visiting around with our own people in their home territory, renewing acquaintance with old friends, making new contacts, and experiencing the gracious hospitality and spontaneous camaraderie which are so characteristic of the Institute membership. It has seemed to me that if these visits were in any way to justify the effort of the members in turning out for such meetings, serious effort should be made through them to accomplish something useful for the Institute and for the society of which it is a part. To that end I have sought informally to evoke from the members suggestions and criticisms out of which the administration of the Institute could be improved. The results of these informal conferences have been brought back either to the administrative officers or to the board, as the case seemed to indicate, and have resulted in action which it is hoped in the long course will somewhat improve the processes of the Institute.

Objective improvement alone has not been a principal purpose in this process. It goes rather deeper than that. The Institute, like all human organizations, in a very just sense belongs to the members. Authority must flow from the periphery to the center, however easy a reverse process may be, and however much in the way of mere efficiency may be said for the latter.

A principal function of the president and of the regional vice-presidents of the Institute is, as effectively as we may, to determine the desires, the thoughts, the wishes of the membership; to bring these into the board meetings and there, in conference and by adjustment, to give them tangible expression.

This, of course, is not a democratic process, and indeed it seriously may be questioned whether, in an organization even of the size of the Institute, spread as it is over the whole extent of this country and representing as it does a highly diversified group of interests, any process of pure democracy can operate. I make bold to suggest that however much the processes of the referendum and the initiative may seem to represent an ideal, they would in effect represent not only an abdication of authority but, even worse, a desertion of responsibility by your officers and committee members. What then must we ask as an ideal form of organization of our professional interests? Would we contemplate an authoritarian national secretary with a society organized about him or a series of presidential officers each for a little time seized of the right to run our organization? Such a central organization would be most efficient without in the slightest degree being effective. It is a habit of administrators to withdraw into the isolation of their ivory towers, in the very process losing all perspective of the ends to which their efficient processes should be directed and perhaps too losing all sight of actualities through preoccupation with or infatuation by the processes of administration.

Full text of the president's address delivered at the AIEE annual meeting held during the combined summer and Pacific Coast convention, San Francisco, Calif., June 26, 1939.

Representative Administration

There is a third scheme of organization which it seems to me is the only effective one, and which we should seek further and further to stimulate in the Institute; that is the process of representative administration through which officers, with particular emphasis on the regional representatives, are carefully selected at once for their ability to exercise good judgment and because of a belief that they initially understand and continuously will keep themselves fresh in a knowledge of the will of their constituencies. Such representatives wisely will consult the membership and will guess correctly as to those things concerning which the membership may wish to be consulted. Consultation will concern general principles and will attempt to make an appraisal of results, but will not seek to burden the membership with the determination of specific details for which the members have selected their representatives.

It is obvious that the specific desires of one section of the membership may easily run counter to the specific desires of other sections, while there may be a complete unity of judgment as to the general objective underlying the more specific elements. This naturally calls for adjustment and compromise on nonessentials in order fully and intelligently to arrive at the main purposes.

Membership Responsibilities

Representative government calls for the highest type of representatives and puts on them a heavy burden both of conscience and of intelligence. Equally it places on the membership a responsibility that does not exist either under an authoritarian or under a theoretically democratic form of organization. To begin with, the selection of representatives by the membership must be responsible and thoughtful, and the members must be willing to bind themselves to every faithful execution by their representatives. Under such a scheme of organization the membership must be willing to view the operations of their representatives, not in detail but as to the general direction of representative determinations, or if in detail, only as details reveal the true character of fundamental consciousness on the part of the representative as to what are his responsibilities. No such responsibility on the constituency exists in a pure democracy since in the latter the individual records his voice directly and as he is moved at the moment, with no necessity for imaginative and sympathetic interpretation.

The process of representative government imposes a further burden on the membership. I have said that it is a principal duty of our presidents and vice-presidents as representatives informally to determine the wishes and the needs of the membership. This is a process that works two ways. If we are to have a representative organization, the members, both individually and through the local subdivisions of the Institute, must seek to make known their desires, their opinions, their criticisms, or their approbation. Beyond that they will best insure a government of the Institute that most truly expresses the will of the membership if they will seek to render service even in the most humdrum and pedestrian matters of the local groups.

No human organization truly can belong to its membership if any large section of its membership believe and act on the belief that it should be a benevolent thing apart from themselves, from which they may draw benefits much beyond the measure of what they contribute of themselves, not merely in an emotional loyalty, but in actual service.

I have taken this occasion to talk at some length about a theory of organization for our Institute, not alone because I believe it to be the one way in which the Institute effectively can be run, but because every principle here involved has, I am convinced, a vastly wider application which I think is sufficiently obvious without further elaboration except for this point. Because we here and in the larger fields of human enterprise do have to deal with frail and actual human beings, preoccupied with a wide range of distracting other activities, because the process of developing an ideal governance must be voluntary, we cannot expect that at any one time any human organization will have realized its best ideals; we must expect that progress toward that realization will be slow, halting, or even at times retrogressive. In times of doubt and discouragement men are prone to ask for a facile formula that will accomplish painlessly all the things that in fact can be brought about only by united, consistent, and plodding effort toward a clearly visioned ideal.

One recalls that the children of Israel in their long wanderings called on Moses to give them a king to reign over them that they might be as the other nations round about them, forgetting that the Lord Jehovah was their king. I suspect that we of the engineering profession are not immune to this natural human tendency to seek an easy, formalized, and institutionalized way of accomplishing those things which can come about only through the collective devotion of individuals expressing the genuineness of their aspirations through a willingness each and every one to do the thing that lies nearest to hand in the full spirit of an ultimate purpose.

We Must Know What We Are After

As in our daily jobs, so also in the profession and in the larger field of human relations, we would do well occasionally to draw aside from the busyness of specific performance and to ask ourselves one fundamental question. May I again refer to the great Law Giver of Israel? You may recall that in the institution of the Passover he suggested that when their children should ask them "What mean ye by this sacrifice," there should be an answer. If our daily jobs, if our purposes for this American Institute of Electrical Engineers, if our conduct as citizens are to be more than a perfunctory performance of ritual, a mechanical service of institutions, we must know what we are after. It is not enough that a more abundant supply of cheap electricity, a more perfect art of communication, a national system of broadcast of television, more efficient

motors, or more dependable circuit breakers should be built by us; it is not enough that stockholders should receive a more nearly adequate return because of our employment; it is not enough that our Institute be larger or financially sounder or that its publications represent a higher level of scientific and literary contribution; it is not enough that our nation shall be secure against enemies at home and abroad or that prosperity shall return to the land. These things are good; they are the things that we must bring about; but we must know in our several jobs, in our professional organization, in our operations as citizens, what we individually have in mind as the ultimate reason for the sacrifices that we are prepared to make and to ask of others. I say we must know what we as individuals have in mind. As an individual, no man can hope to know the absolute ideal toward which his efforts actually are being directed. He can only know what he thinks should be the ideal, and in this his thought will change as he grows in experience and in wisdom. Since, then, the ultimate objective of effort is individual and changing for each individual, it can never be expected to become a formulated expression.

Is this all fine-spun, unpractical philosophizing unworthy of consideration by the members of a most realistic profession? I think not.

There is a quality in men as they work at their jobs; there is a quality in professions as such; there is a quality in the citizenship of each nation that inevitably is expressive of inner light which unconsciously, unobtrusively gives direction to specific acts of performance and which in the aggregate accomplishes the greatest influence in human affairs. It may defy definition, but it is patent to all. Greek civilization, mediaevalism, the American spirit, each has a significance, not because of the things that were done, but because of an unexpressed inner urge. The mentioning of the name of an individual corporate enterprise calls up in your minds and in mine pictures of something, not expressed in the sales literature or in the product, which *is* that enterprise. Name one of the professions or one of the nonprofessional callings and immediately there springs into mind an intangible thing which is the inner essence of that vocation.

Let's leave it at that.

I recommend to the membership of the Institute individual responsibility, individual work, and an organization developed along representative lines, but above all else that, in the odd moments between wakefulness and breakfast, we occasionally give some thought to why we are engineers and why engineering should be a part of the processes of human life.

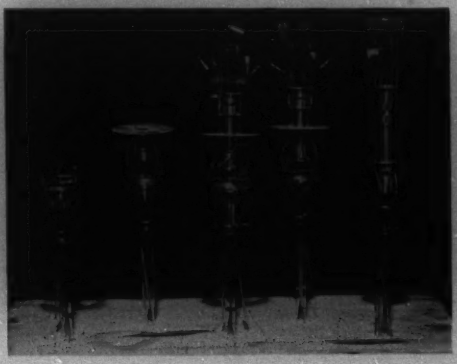
Nickel in Television

THE use of nickel and certain nickel alloys for the production of cathode-ray tubes is proving an important factor in the practical development of television. The cathode-ray tube, which translates electrical impulses into visual patterns, is an essential element of modern television sets. Within the tube, electrons emanating from heated metal are formed into a beam and projected on a fluorescent screen at the wide end of the tube. The screen is illuminated at the point of impact, and the beam, swinging across it at tremendous speed, creates the television image.

Great skill is required for the production of cathode-ray tubes, which are made up of an intricate assembly of glass and metal parts, subjected to severe tests before being used. To meet the requirements of cathode-ray-tube manufacture, a metal must have certain mechanical, electrical, and chemical characteristics. It must:

1. Be amenable to a wide variety of fabricating operations,
2. Be sufficiently strong, even in the softest temper, to avoid deformation during normal handling and use.
3. Remain strong at high temperatures.
4. Have a high modulus of elasticity, particularly at high temperatures.
5. Permit strong spot welds.
6. Be rust proof and corrosion-resistant.
7. Resist warpage and distortion regardless of high temperatures.
8. Have certain required electrical properties, especially proper electron-emission characteristics.
9. Be low in contained gas and readily degasified at moderate temperatures.

Experience in the production of radio tubes, X-ray tubes, and cathode-ray tubes for other purposes demonstrated the ability of nickel to meet the requirements of



television. The metal parts of cathode-ray tubes for television are made of pure nickel, supplemented by nonmagnetic alloys with high nickel content, such as "K" Monel and Inconel. The illustration shows a group of assemblies as inserted within the tubes.

Signaling on Electric Railroads

S. E. GILLESPIE

A survey of recent developments in signaling practice, with some consideration of their foundations and growth

WHILE this article is concerned primarily with recent developments in railway signaling, brief reviews of certain phases of the subject have seemed desirable, since this branch of engineering has developed a terminology in some respects peculiar to itself. Railway signaling may be divided into two nearly equal parts: circuit schemes to accomplish certain effects, and the apparatus with which the effects are produced. The designs of both parts are interdependent and proceed together, always with the objectives of safety and reliability. The recent developments to be considered are coded track circuits, automatic train control and cab signals, centralized traffic control, and route interlocking.

Track Circuits

The track circuit is the foundation of nearly all modern signaling, upon which the superstructure is built. It consists essentially of a metallic circuit, in which the running rails are the principal conductors, having a current supply at one end and a relay at the other. For purposes of track circuiting, the track is cut into sections as desired by inserting insulations at the joints; these sections may be a few feet in length or they may be a mile long, or even longer, as required. The rails are bonded together on each side of the track to insure continuity of the circuit. When the relay is supplied with enough current, its contacts close, but when a train is on the track circuit, it short-circuits the rails and shunts out the relay current to approximate zero; the relay contacts then open by gravity and interrupt any circuits passing through them.

The track circuit has proved so reliable a detector of the presence of a train that it has superseded every other rival device. It has the further advantage of indicating rail breaks when they occur.

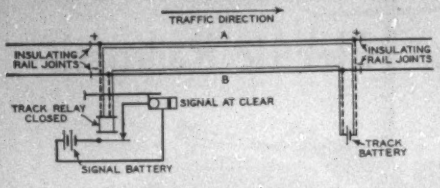
Track circuits were first applied on tracks used by steam trains and were energized from batteries. When electric propulsion of cars and trains was introduced, and the rails were made to carry the return propulsion current, means had to be devised to provide a continuous propulsion return circuit and to render track relays immune to the return propulsion current.

The solutions found were these: to take care of the propulsion return current, one rail may be left uninsulated while the other is insulated into sections. Track circuits installed in this way are called single-rail track

Address presented before the transportation group of the AIEE New York Section, New York, N. Y., November 15, 1938.

S. E. GILLESPIE is with the Union Switch and Signal Company, Swissvale, Pa.

Unoccupied: The track circuit current that holds the track relay closed flows from the track battery through the rails A and B to the track relay



Occupied: As train enters block section, the wheels shunt track circuit current from the track relay. Signal circuit is open and signal moved to "Stop"

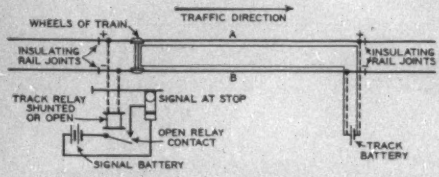


Diagram of d-c track circuit

circuits. They are feasible only where the sections are relatively short and the return current can be carried by one rail, or where a supplementary return circuit is provided.

Where single-rail track circuits are not feasible, impedance bonds are used to connect the rails of each track circuit to those of the next. Impedance bonds are essentially large choke coils connected across the track at each end of the track circuit, with center taps connecting to center taps on similar coils in adjacent track circuits. Of course the winding must have sufficient conductivity to carry the return current. For railroads with d-c propulsion, track relays were devised which operate on alternating current but not on direct current; the most popular relay for this condition is the two-element vane relay. For railroads having a-c propulsion, track circuits are energized with alternating current of a frequency different from that of the propulsion current, and frequency-selective relays responsive to the signaling frequency but not to the propulsion frequency are employed. The most successful relay for this purpose is the centrifugal frequency relay working on the weighted-arm governor principle. Even if 25-cycle current strays into this relay the motor will not spin the weights fast enough to close the contacts.

Among the railroads entering New York City, the New York Central, the Delaware, Lackawanna, and Western, the subways, and the elevated have d-c propulsion and track circuits operating on alternating current; the New York, New Haven, and Hartford, with a-c 25-cycle propulsion, has track circuits operating on 60 cycles and centrifugal frequency relays. The Pennsylvania Railroad has both kinds of propulsion current and both kinds of track circuits. and in addition coded track circuits.

Coded Track Circuits

When automatic cab signals and train control arrived, requiring receiving apparatus on the locomotive to be actuated by electric impulses inductively picked up from the rails while the locomotive is in motion, and requiring the locomotive apparatus to be responsive to as many as four different conditions, a new problem had to be solved. It was met by what is known as the code system, in which alternating current of 100-cycle frequency is fed to the rails through interrupters, or code transmitters, which interrupt or modulate the track current at as many different rates as required to convey the different messages. At first this coded train-control current was superimposed only when needed upon the regular track current, but the latest installations have largely dispensed with the former track-circuit apparatus and use coded current continuously. This code system may be used for controlling either wayside or cab signals or both, on railroads with any kind of motive power; consequently it is known as the universal coded track-circuit system.

This new system has a number of advantages over any previous development. It can be used to transmit three or four or more indications if required, over the rails only, without any line control wires at all. Since it employs a special frequency, different from any commercial frequency likely to be found in the vicinity, it is peculiarly free from the danger of interference. The receiver is tuned to the signal frequency and will not respond to any other; the energy, even though of proper frequency, must still be coded to produce any "Proceed" indication. Another factor of safety is that the track relay must continuously open and close its contacts to produce any "Proceed" indication, so that any interference with this uniform motion, such as electrical interference or mechanical failure or stoppage, will result in the most restrictive signal indication. Still another safety factor is that it is easier to insure a reliable shunt of the rails by a train with a track relay which is being continuously de-energized and re-energized, than with one which must be de-energized only. With the coded track circuit, it is relatively simple to put in cut sections when this is necessary on account of the length of the block, or to provide for the control of highway-crossing protective devices.

Finally, the elimination of line wires from the signal-control system removes a possible cause of signal interruptions during severe sleet and wind storms.

A coded track circuit has the following elements: a source of 100-cycle energy; an interrupter or code trans-

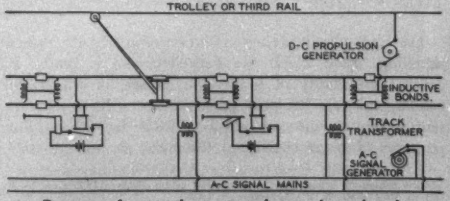


Diagram of a-c track circuit with impedance bonds

mitter capable of interrupting the 100-cycle track current at rates of 75, 120, or 180 times per minute; connections for feeding this intermittent energy to the rails; at the receiving end, a filter resonant to 100 cycles and blocking the propulsion current, and a rectifier; a d-c relay which will follow with its armature the code impulses received through the rectifier unit; a decoding transformer; a home relay which becomes energized whenever the code-following relay is working; one or more relays, as required, tuned to operate selectively on impulses occurring at rates of 120 or 180 per minute, for transmitting higher speed indications.

This arrangement is analogous to a broadcasting station transmitting on a frequency of 100 cycles per second, the carrier wave modulated or interrupted at rates of 75, 120, or 180 times per minute, and a receiver tuned to 100 cycles. The incoming carrier is rectified or detected. Three tuned audio circuits, or any required number, would respond selectively to their peculiar notes. The output is of frequencies much lower but corresponding to relative audio frequencies.

At the sending end of the circuit the frequency of modulation is automatically selected according to the conditions ahead affecting the safety of trains, and at the receiving end the signals are caused to display corresponding indications.

If a train intervenes it will short-circuit the rails, shunt out the track-circuit current, cause the signal governing that section to present its most restrictive indication, and cause signals in the approach to display appropriate cautionary indications.

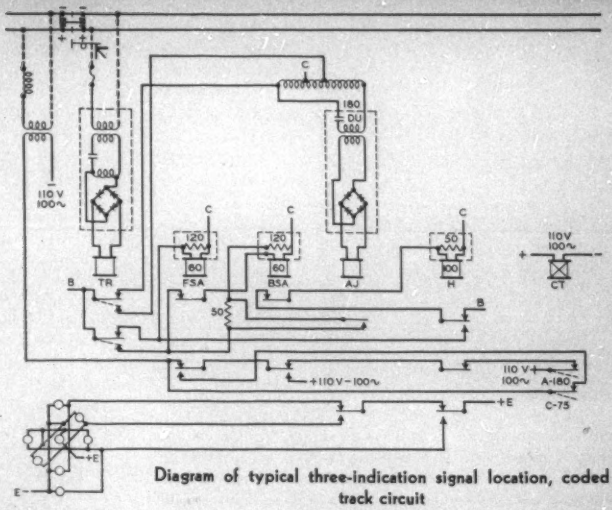


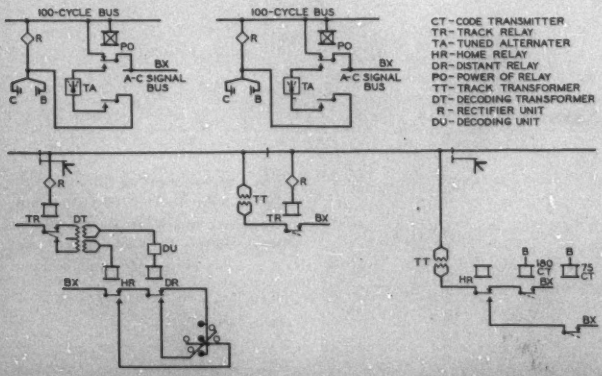
Diagram of typical three-indication signal location, coded track circuit

In order not to complicate the description, 100 cycles has been given as the universal track-circuit frequency for coded track circuits. However, other frequencies could be and have been used. One installation employs 91.6 cycles.

Automatic Train-Control and Cab Signals

The receiver previously described is the type required to control a three- or four-indication wayside signal. For a cab signal in a locomotive, receiving coils, attached to the locomotive just above the rails in front of the first wheels, pick up the 100-cycle current by induction. The coded energy is next amplified and then decoded as in a radio receiver and used to energize the relays which light the appropriate indications in the cab signal. These cab-signal indications duplicate the wayside signals as they are passed and retain them to the next signal, provided there has been no change in conditions ahead. Automatic block and cab signals are always governed by conditions ahead, produced by trains, or the absence of trains, and the positions of switches and turnouts. If any change occurs ahead within the control range, both wayside signals and cab signal immediately respond to it, even though the locomotive is moving forward at high speed.

Continuously controlled cab signals have an advantage over wayside signals in that the engineman receives any change in the indication at once, without having to wait



Schematic diagram of coded a-c track circuit, for three-indication signal system

Light signal, impedance bonds, automatic stop, and train, Delaware River Joint Commission

Propulsion: 600 volts, direct current. Signal current: 60 cycles

Track relay: two-element vane

until he can see the next wayside signal. If the change is to a more restrictive indication he is warned by an audible signal, such as a whistle, and can take precautions immediately; if the change is upward to a higher speed, he can promptly increase his speed, thus saving time.

The advantage to an engineman of having a continuous signal just in front of him in the cab when he is driving ahead through thick weather is apparent.

After apparatus selectively responsive to 75 code, 120 code, 180 code, and no code has been installed on the locomotive it is just one more step to add a speed-governor with electric contacts and apparatus which will affect the air brakes when the actual speed exceeds that assigned to the relative signal indication—providing automatic train control.

Centralized Traffic Control

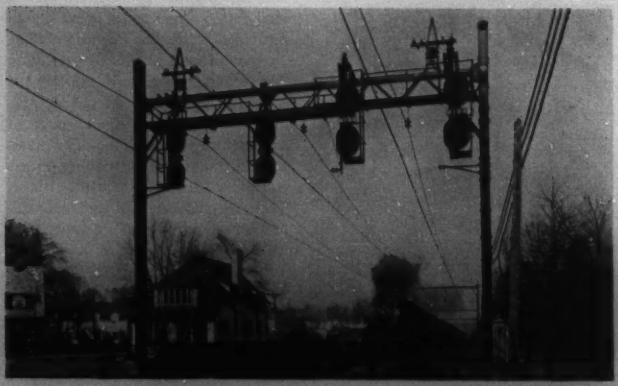
Centralized traffic control is a system by which all the main-line track switches and signals in a district, or even an entire division, are manipulated from a central control board. It may be regarded as an evolution from power interlocking and automatic block signaling combined. As in interlocking practice, trains stop or proceed on signal indication alone, without written orders, and without regard to the priority of other trains.

The operator has before him an illuminated diagram or track model simulating all of the tracks, switches, and signals under his control, with indication lights showing the position and movement of trains as well as the position of track switches, and signal indications. Small thumb switches enable him to control signals to stop trains, or to notify them to proceed, and to operate track switches as required to divert trains into sidings or to other tracks to avoid other trains. Remote signals and switches are controlled by means of impulses generated automatically by a relay code system and sent out over a pair of wires, and return indications of the position of switches, the indications of signals, and the positions of trains come in automatically over the same wires. If several messages try to use the wires simultaneously, those coming in later are automatically stored and withheld until the circuit is free. Precedence is given to outgoing controls over incoming indications. Every safeguard developed in power interlocking and in automatic block signaling is incorporated in the system, so that no error the operator can make will do more than stop and delay a train.

An automatic device records on a moving time-chart the passage of trains over established registering points.

Outlying switches and signals are operated by local power, and the switches may be hand operated if necessary. Conveniently located telephones enable train crews to communicate with the operator if they are stopped at a signal and are in doubt about what to do. In electrified territory trolley sectionalizing switches or other apparatus can be regulated from the control panel and this is being done.

Centralized traffic control assists materially in quick handling of trains, reduces stops and delays, and increases track capacity wherever it is used.



Signal bridge showing R2 color light signals with 10-volt 18-watt lamps, impedance bonds, signal transmission line, Delaware, Lackawanna, and Western Railroad

Propulsion: 3,000 volts, direct current

Signal transmission: 2,300 volts, 60 cycles

Track relay: two-element vane

Track circuits: single rail up to 1,000 feet, double rail, 1,000 to 3,000 feet

Signal bridge showing color light signals in triangular arrangement, approach-lighted, with 10-volt 18-watt lamps, The Reading Company

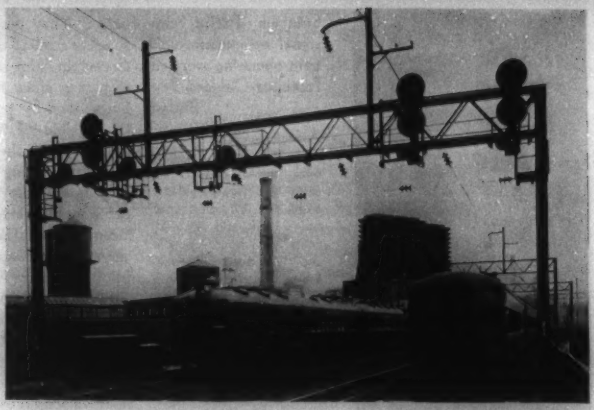
Propulsion: 12,000 volts, 25 cycles

Signal transmission: 4,400 volts, 60 cycles; 4,400 volts, 100 cycles

Track circuits: single rail, up to 1,200 feet; double rail up to 6,500 feet

Track relay: centrifugal frequency polarized line control

Wayside signal indications in automatic territory: "clear"—green over green; "approach restricting"—yellow over green; "approach"—yellow over red; "stop"—red over red



Route Interlocking

Interlocking began with the use of a group of heavy levers mechanically connected to switches and signals in order to operate them from a convenient central point. The levers were interlocked to insure against setting up conflicting routes, or giving "Procced" signals under unsafe conditions. In the course of time compressed-air cylinders or electric motors were attached to the track switches and semaphore arms, and the levers, still interlocked, merely served to actuate electric circuit controllers. Much ingenuity was shown in the design of circuits and protective devices to insure against human errors, and to prevent ill effects from failures of apparatus. Gradually a complete system of electric checking and proving, including electric track-circuit locking, grew up around power-interlocking systems, until it became evident that the mechanical interlocking between levers could safely be left out, and the control machines simplified thereby. At that stage power interlocking becomes relay interlocking, but it is still necessary to operate a sequence of control levers in order to set up a route through a network of tracks, and to restore them before setting up another conflicting route.

The latest development is route interlocking. An illuminated diagram of the track network included within the controlled area is fitted with push buttons at each end of each track route. In order to arrange all of the switches and signals for the passage of a train the operator need only push two buttons, one at the point where the train enters and one at the point where it leaves. The diagram illuminates to show the route established and the push button at the entering point lights up green when the entering signal has cleared; the lights on the push button and the different sections of track turn red as the train occupies the various sections and then go out in succession as the train passes through. The passage of a train through a route automatically sets the signal at "Stop" and leaves the switches behind it released for further use.

The operator can make no dangerous errors, since a route once established is locked up and automatically locks out all conflicting routes until the train passes through and releases it, or until the line-up is intentionally cancelled after a safe time interval. But if the operator wishes quickly to set up another route over that being vacated by the first train he can do so; the route is automatically released behind a train, section by section.

This method is adapted to close-lying areas and direct-wire control. There is no limit to the size of the system that can be served by one control panel, although naturally the complexity of circuits grows with the number of possible routes.

Types of Wayside Signals

The mention of railroad signals is likely to call up a mental picture of a signal with semaphore arms uplifted or outstretched, and there are many thousands of these signals doing faithful service today. But all recent developments have to do with electric-light signals.

Light signals are of various types and kinds depending

Automatic train stop with engaging arm on car, Independent Subway, New York, N. Y.

Southern Pacific cab signal on multiple-unit train operating over San Francisco-Oakland Bay Bridge

Aspects: green and 35, 35 miles per hour; yellow over green and 25, 25 miles per hour; yellow and 17, 17 miles per hour; red and 11, 11 miles per hour; purple and NS, out of service; white in conjunction with any of the first four, cautionary

upon their location and the distance from which they must be seen and understood. A subway does not require a signal of the power and range demanded on a high-speed railroad in bright sunlight.

Modern long-range light signals employ small concentrated-filament lamps carefully focused behind lenses. Although using only 10 to 18 watts, they are visible in ordinary clear weather at distances of a mile or more. These lamp-and-lens units are carefully focused in a dark room by the manufacturer before shipment and are not adjustable. The lamps are made to a precision standard and can be renewed without destroying the focus. It is common practice to equip these lamps with a secondary filament of lower wattage than the main filament, to provide against burnouts.

Several railroads have developed distinctive types of signals—for example, the position-light signal of the Pennsylvania Railroad, and the color-position light signal of the Baltimore and Ohio Railroad—but many use the color-light signal which gives its messages in colors only.

Railway light signals must meet certain requirements not filled by street traffic signals or by automobile headlights: They must not reflect other lights, even sunlight, so as to display a color not intended; they must conform to certain color standards; they must be very economical of power, since in many cases the source of power, perhaps stand-by power, is a primary battery. They must be capable of being accurately focused and carefully pointed to get the maximum effect from minimum wattage.

Signals having separate lenses and lamps for each color may not employ reflectors. However, one type, called the searchlight signal, has only one lens system and one lamp. It contains a reflector and an internal color-changing mechanism, and can display any one of three colors.

Electric railroads with catenary overhead systems and bridges supporting the catenary and power lines present a problem in locating signals to good advantage. Light signals are peculiarly suited to this situation, since they occupy little space, require infrequent attention, are not easily obscured by intervening overhead work, and have no external moving parts.

Signaling on Bay Bridge

This article should not conclude without referring to the signal work associated with the San Francisco-Oakland Bay Bridge. That installation includes coded continuous cab signals with automatic speed control at four speeds, without wayside signals between terminals, and a push-button or route interlocking at each terminal. The headway provided for is 63 1/2 seconds at 35 miles per hour. The enforced speed limits are 35, 25, 17, and 11 miles per hour. For "clear" the cab signal illuminates green with a numeral 35. For "approach restricting" another light comes on, upper half yellow and lower half green, with the numeral 25. For "approach" the cab-signal indication is yellow with numeral 17. The most restrictive indication is red with numeral 11, below which speed a train may proceed expecting to find another train ahead. If a train is proceeding at a prescribed speed and the cab signal changes downward, the motorman must immediately apply service brakes to forestall an automatic application. One-block overlap on the control of the minimum-speed indication provides stopping distance of at least one block after the cab signal has changed downward to that indication. There are of course wayside home signals and other wayside signals at the terminal interlocking plants.

Centralized-traffic-control panel at Columbia, Pa., electrified territory, Pennsylvania Railroad

A Method for Determining the Efficiencies of Small Motors

JOHN L. C. LÖF
ENROLLED STUDENT AIEE

FRACTIONAL-HORSEPOWER motors have been developed for many uses which cause their characteristics to differ widely from larger motors. Usually they are designed for constant-load operation, but some are made to have large starting torques and others to run at constant speed. Naturally these motors have a much smaller efficiency than the larger ones, and the methods used for determining the efficiency of the larger motors are not practical for the small ones.

A most common method for determining the efficiency of small motors is the Prony brake method, in which the output in watts is calculated from a speed-torque formula and the input is measured directly by a wattmeter. The torque is measured by a friction brake applied to a drum, and the speed read by a tachometer or revolution counter. The chief disadvantages of this method, when applied to small motors, are:

1. Difficulty in maintaining a constant torque on the drum.
2. Introduction of additional friction into shaft by radial pressure.
3. Difficulty in reading speed correctly, and introduction of a small load by the speed-indicating device not measured by torque indicator.

With a view to eliminating these objections, the following method was developed which does not involve either the measurement of speed or torque. It makes use of the eddy-current-brake idea, but actually measures the heat produced by eddy currents instead of torque. A brass disk about $^1/_4$ centimeter thick and 17 centimeters in diameter has its central part removed so as to leave a flat ring about 4 centimeters in width. This disk is placed in a recess between two accurately machined bakelite plates, which completely enclose it. In the recess between the disk and the bakelite plates is a layer of felt which helps to insulate the brass disk from heat loss due to conduction to the bakelite plates. The disk is mounted on the shaft of the motor to be tested and rotates without vibration (figure 1).

Load is applied to the motor by an arrangement of four equally spaced electromagnets, the poles of which are on opposite sides of the rotating disk with suitable clearance. A direct current excites the magnets which set up eddy currents in the disk rotating through the field. The load applied to the motor is adjusted by varying the magnitude of the field. The power output of the motor is then the actual amount of heat generated by the eddy currents in the disk instead of the torque produced in the field. To determine the heat produced, the weight of the disk and its temperature rise over the interval during which the field is applied are found. The temperature rise of the disk is computed by the use of either a resistance thermometer or a thermojunction. In the first method, use is made of a groove around the periphery of the disk in which is wound about 38 ohms of very fine, enameled copper wire. The ends of the coil are attached to two binding posts on the bakelite plate. The temperature change of the disk then may be computed by measuring with a Wheatstone bridge the resistance of the wire at the start and finish of the run using the equation:

$$R_t = R_0(1 + 0.00427t_1)$$

Upon rearranging, this becomes:

$$\Delta t = \frac{R_t - R_0}{R_0}(234.5 + t_0) = \text{temperature change}$$

The second method of computing temperature rise is by the use of a thermocouple soldered to the disk. A Chromel-Alumal junction was chosen for this purpose because of its high thermoelectric power. The electromotive force produced is measured by a low-resistance microammeter, which reads temperature change by means of a calibration curve that is determined by placing the cold junction at various known temperatures while keeping the disk at a constant known temperature (figure 2).

This latter method is preferable because it is easier to operate although it requires slightly more preparation of apparatus. Hence, only this method is considered from here on. However, both methods are subject to a cooling effect which takes place during the interval between the end of the time of application of magnetic field and the reading of the recording instrument. This is due to slow conduction of heat through the insulation (figure 3). This difficulty is readily overcome in the following way: The microammeter deflection is recorded for successive small time intervals, which in this case were 15 seconds.

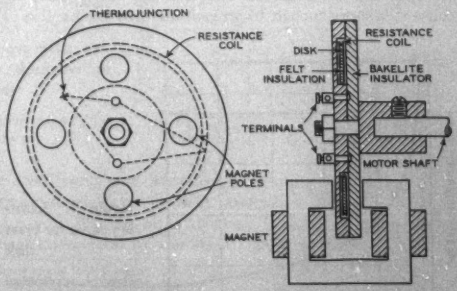


Figure 1. Diagram showing arrangement of apparatus for measuring efficiency by the eddy-current-heat method

This paper received the AIEE national prize for Branch paper for the academic year ending June 30, 1938.

JOHN L. C. LÖF received the degree of bachelor of science in electrical engineering from the University of Denver and is now a graduate student at the Massachusetts Institute of Technology, Cambridge.

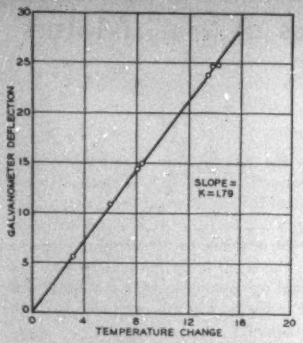


Figure 2. Calibration curves for Chromel-Alumel thermojunction

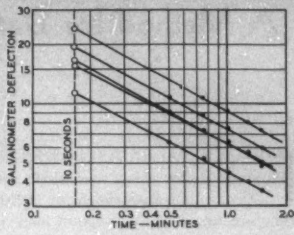


Figure 4. Typical log-log curves for determining deflection of temperature-measuring galvanometer at time of removing magnetic field

Then these results are plotted on log-log graph paper using the zero-time point as the time at which the magnetic field was first applied. Series of tests covering various time intervals show conclusively that these log-log curves are straight lines, all having the same slope over the range considered; therefore, by drawing a straight line through the points obtained, the expected theoretical deflection at the time of removing the magnetic field is obtained by extrapolating the line (figure 4). Then the true temperature change is found from the calibration curve. However, this lack of perfect insulation and the resultant cooling of the disk should not be considered as a serious disadvantage because this prevents the disk from becoming overheated after many trials.

After the true rise in temperature has been determined, the heat output generated is easily computed from the equation:

$$W_o = \frac{M \times C \times \Delta t}{0.239 \times T} \text{ watts}$$

where

Δt = temperature rise
M = mass of disk
C = specific heat of metal
T = time of applying field

Experimentation has shown that the best time interval for applying the magnetic field is about ten seconds because it is short enough to prevent any appreciable loss of heat from the disk while running and still long enough to permit accurate timing. Also, this short time does not heat the motor appreciably on heavy overloads. The 10-second period may be timed accurately with a stop watch. A field of about 70,000 maxwells is found to be sufficient for a $^1/_{15}$-horsepower motor.

An efficiency curve may be obtained by varying the exciting current of the magnets so that the eddy-current heat output will be varied. The efficiency, of course, is determined by computing the ratio of output to input, the output watts being computed as described and the input watts determined by a wattmeter (figure 5).

This method as developed could easily be applied in industry, as the equipment is neither complicated nor expensive. Testing on heavy overloads may be done very easily because the time of loading is very short and there are no heavy radial forces acting to introduce large amounts of shaft friction. Also, the efficiency of a motor at any temperature can be found readily as the method causes very little change in the motor temperature during the short time intervals used.

The accuracy of this method is probably equal to that of other methods because there is little opportunity for introducing errors. Being entirely independent of speed or torque measurement, the method is not subject to inaccuracies here. Practically no additional friction is added to the motor with increase of load, and the motor does not become heated appreciably during the test. Consequently, the values of efficiencies found by this method might be expected to be slightly higher than those obtained in other ways. Also, the motor runs entirely free, and the disk introduces only slight windage loss. These advantages indicate that this is a practical and promising method for finding efficiencies of small motors.

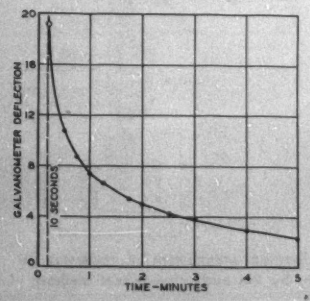


Figure 3. Cooling curve for brass disk

Time of application of field—10 seconds; output—104.4 watts

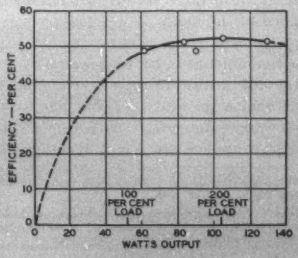


Figure 5. Efficiency of a 1/15-horsepower split-phase resistance motor, as determined by the eddy-current-heat method

The Electric Strength of Fibrous Glass

A. GEMANT F. A. GLASSOW

The ideal, and probably future, use of fibrous glass for electrical insulation is without an organic filler. Therefore, it is important first to know its electric strength in unimpregnated condition. Test results show its high qualities at elevated gas pressures and temperatures.

THE advantage of inorganic electrical insulators as compared with organic ones has been frequently emphasized by investigators, mainly with regard to their stability against oxidizing and other deteriorating agents. Unfortunately, one of the chief organic insulators, namely paper, valuable for its flexibility and porosity, could not until recently be replaced by an inorganic material. The introduction in the last few years of textile glass seems to be a promising step toward filling this gap. Its importance and usefulness is described in several recent publications.[1–4]

The chief use of fibrous glass at present is in combination with varnishes and resins, since the electric strength of the textile alone is too low for most purposes. It should be pointed out, however, that the essential advantage of the glass, namely its inorganic nature, is lost in this combination. The ideal insulator will be textile glass, impregnated with the inorganic resin of the future.

It is not meant by this statement that the organic material will affect in any way the deterioration of the glass fiber itself; also the combination of glass with varnish is admittedly superior to the combination of cotton or asbestos with varnish. But the full and theoretically maximum advantage of the fiber glass can be obtained only in combination with an inorganic filler.

In face of this requirement it is important to gather more information on the dielectric breakdown strength of glass cloth alone, without its organic filler. It is known already that the strength is practically the same as that of an air gap of equivalent thickness. It was the authors' purpose, therefore, to extend this information with regard to the effect upon the breakdown strength of several factors, such as the density of the woven structure, the type of voltage, whether alternating or continuous, the air pressure, and the temperature. This article presents the results of this research, together with some conclusions to be drawn.

Apart from the necessity of knowing the behavior of the glass textile without an organic filler, this information might be of direct use in the field of modern air cables,[5–6] consisting of paper and air under elevated pressure. The use of fibrous glass combined with air at high pressure would then be a first model of a purely inorganic "impregnated" insulation.

General Results

Four different makes of textile glass were used in this investigation, denoted by numbers 1 to 4; 1 and 2 refer to cloths, and 3 and 4 to glass tapes. The corresponding specific weights are 0.8, 1.2, 0.6, and 0.3 pounds per square yard, and the corresponding thicknesses 20, 30, 10, and 5 mils. In the breakdown experiments, however, one plane and one spherical electrode were used, and the actual separations, due to compression, were somewhat smaller than the nominal thicknesses of the test specimens. In preparing the curves the actual separations were used, as determined by means of a plane and sphere micrometer.

The samples were not specially conditioned for the tests, as some measurements showed that specimens dried at 120 degrees centigrade did not yield higher values for their electric strength.

In the a-c tests the voltage was measured by means of a precision transformer of ratio 120 to 1 and a voltmeter, and in the d-c tests by means of a liquid high-resistance potentiometer in connection with a 750-volt static voltmeter. Short-time tests were carried out throughout the whole work.

The general results of such measurements are indicated in figure 1, a-c data being peak values. Each point represents the average from several individual data. The dotted line represents the values of a corresponding air gap, the data being taken from the literature.

In order to interpret the results, the following facts should be recalled. In paper, or in a textile like glass cloth, the insulation consists of a large number of thin layers of the solid, connected in series, alternating with similarly narrow air gaps. The field strength in the air is then higher than it would be in air alone, because of the higher dielectric constant of the glass. This circumstance will

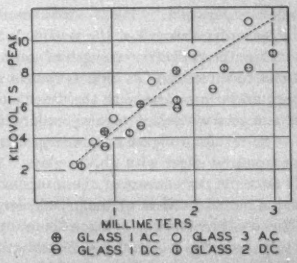


Figure 1. Breakdown voltage of fibrous glass versus thickness of layer

Dotted curve is for an air gap

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The authors are indebted to Professor Edward Bennett (A'01, F'18) of the University of Wisconsin for facilities placed at their disposal.

For numbered references see list at end of article.

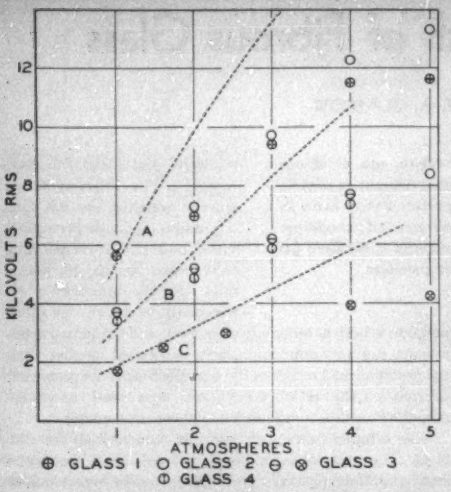

Figure 2. Effect of gas pressure on the a-c breakdown voltage of fibrous glass

A—Glasses 1 and 2; thickness of layer 1.8 millimeters
B—Glasses 3 and 4; thickness of layer 1.0 millimeter
C—Glass 3; thickness of layer 0.5 millimeter
Dotted curves are for air gaps

tend to reduce the electric strength of the structure, as compared with air.

Ionization and subsequent arcing, however, occurs in the narrow air gaps, the ignition field strength of which increases considerably with decreasing separation. The cross section of the actually open air channels is also very small, and it is known that the electric strength of such channels is higher, as compared with an open air gap of the same separation.[7] These circumstances will tend to increase the strength of the textile, as compared with air.

Thus the dielectric strength of unimpregnated paper is twice to three times as high as that of a corresponding air gap, and it increases with the density of the paper. This is in accord with the foregoing explanation.

The results in figure 1, however, do not indicate such a pronounced effect with fibrous glass. The reason for this is that the dimensions of the interspaces in fibrous glass are some two orders of magnitude larger than in paper. The a-c breakdown voltages lie a little above the air curve, and the d-c voltages somewhat below. This fact, too, can be explained on the foregoing basis. The field distribution for alternating current is controlled by the dielectric constants of the two components (glass and air), but for direct current, by their conductivities. The former ratio is about 5, whereas the latter is certainly larger; the divergence between the d-c values and the a-c maximum ones is, therefore, easily understandable.

The density of the structure was somewhat closer for glasses 3 and 4 than for glasses 1 and 2 (compare the figures for weights and thicknesses as given previously). The values obtained with glass 3, however, are only slightly higher than those obtained with glass 1. The reason is that a pronounced difference, due to texture, cannot be expected in this range of relatively large porosity.

It follows from these observations that a denser structure of the glass textile would be desirable from the standpoint of its electrical application, particularly if the glass were to be used without an impregnating material.

Pressure Effect

The next point was to find out the effect of the air pressure upon the electric strength of glass cloth. Previous research on paper[7] has revealed that the voltage-pressure curves for paper and air cross each other. Normally the curve for paper is situated above that for air, but beyond a certain pressure the paper becomes a worse insulator than air. The reason for this effect is that the breakdown strength of air is a function of separation times pressure; the beneficial effect resulting from the thin interstices, therefore, gradually decreases when the pressure is being increased.

The experiments on glass cloth were carried out in a cylindrical cast-iron tank with a lid bolted to the main body. The lid contained a porcelain bushing, serving as the high-voltage lead, the grounded lead being connected to the cylindrical body itself. Compressed nitrogen was used to provide the necessary pressure, the magnitude of the latter being read on a manometer attached to the pressure pipe.

Figure 2 shows the results obtained with alternating current, for glass cloth of three different thicknesses. The air-gap curves corresponding to each of these thicknesses are shown as dotted lines.

The values for glass lie only a little above the air curve for the normal pressure of one atmosphere, but for higher ones they all lie below the air curve, though the increase of the electric strength with pressure is very pronounced

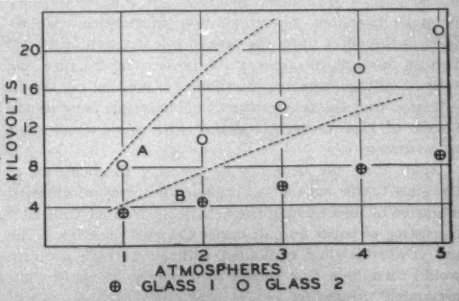

Figure 3. Effect of gas pressure on d-c breakdown voltage of fibrous glass

A—Glass 2; thickness of layer 2.4 millimeters
B—Glass 1; thickness of layer 0.9 millimeter
Dotted curves are for air gaps

and nearly linear. The crossing of the curves occurs between one and two atmospheres pressure, due to the high porosity of the fibrous glass. Nevertheless, the latter could well be used in this combination, and would be certainly superior to paper in that occasional ionization will do less damage to glass fibers than to organic cellulose fibers.

Figure 3 shows results of some d-c tests. The air gap curves again are indicated, and the trend of the data is similar to that with alternating current. The divergence between the glass and air curves is here even more pronounced, and crossing apparently takes place below the normal pressure of one atmosphere.

Temperature Effect

One of the chief advantages of fibrous glass is the possibility of its being used at higher temperatures. Thus some puncture tests have been carried out from room temperature up to 350 degrees centigrade. A small electric oven was used for this purpose, a porcelain bushing at the top serving as the high-voltage lead. An asbestos-insulated Nichrome wire of about eight-ohm resistance provided the heating element. The electrodes were of brass, the bottom one being plane and the top one spherical.

Figure 4 shows some of the results, a-c data being effective values. The corresponding dotted air curves start

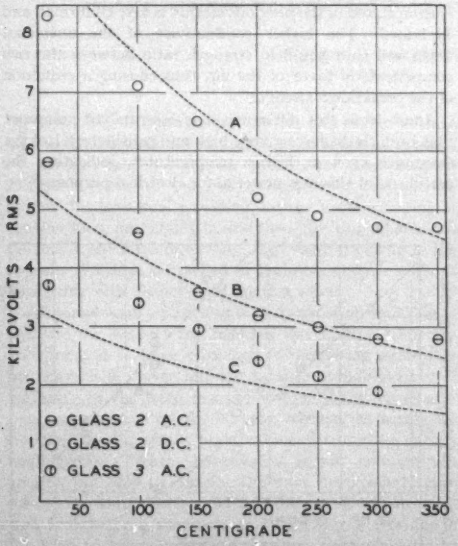

Figure 4. Effect of temperature on breakdown voltage of fibrous glass

A—D-c test on glass 2; thickness of layer 2.4 millimeters
B—A-c test on glass 2; thickness of layer 1.8 millimeters
C—A-c test on glass 3; thickness of layer 1.0 millimeter
Dotted curves are for air gaps

Table I. Puncture Values in Kilovolts (Effective) of Oil-Free Glass Fabric 4, Thickness 0.7 Millimeter

Temperature (Degrees Centigrade)	Washed Tape	Heat-Treated Tape	Air-Gap Value
25	3.05	3.1	2.4
150	2.65	2.6	1.7
350	2.1	2.05	1.15

with the known data for room temperature, while the curves themselves are calculated on the basis that the electric strength is proportional to the density of the gas, that is, to the reciprocal of the absolute temperature, if the pressure is constant.

In agreement with the previous results, the d-c values lie somewhat below, and the a-c values above the respective air curves. They generally follow the latter quite closely, thus indicating that glass textile is, indeed, a very useful insulator for higher temperatures, since it does not deteriorate, and that the decrease of the electric strength of unimpregnated glass with increasing temperature is due only to the normal behavior of the air in the interspaces.

Fibrous glass contains a small fraction of mineral oil, which is used as lubricant in the weaving process. However small this fraction might be, its presence is certainly not desirable, since it will oxidize at higher temperatures, thus to a certain extent obviating the high heat resistance of the cloth itself. The fact that the oil is situated on the surface of the fibers is a special disadvantage, as the (internal or external) surfaces represent the spots of least resistance for any dielectric.

The deterioration of the oil at elevated temperatures can easily be seen from the brown discoloration the fabric assumes when heated above 150 degrees centigrade. This burning of the oil might also occur if the glass cloth were impregnated with a resin which itself withstands that temperature.

In order to find out whether this small proportion of oil has any detectable influence upon the electric strength of the glass cloth, it was necessary to compare the normal fabric with an oil-free specimen. There are two ways to remove the traces of oil from the fabric, namely, by washing the cloth with an alkaline soap solution, or by heating it to 450 degrees centigrade, thus burning off the oil completely.

Glass tape 4 was, in fact, a specimen furnished by the factory in oil-free condition, partly washed, partly burned off. A number of single layers having a total thickness of 0.7 millimeter were tested by means of alternating current, and the results for three different temperatures are shown in table I, together with the corresponding values for an air gap.

The improvement, as compared with air, seems decidedly greater than for normal glass, as shown in figure 4. The 1.0-millimeter curve (*C*) for instance, shows an improvement of 30 per cent for 150 degrees centigrade, as compared with 53 per cent for the oil-free samples.

In order further to verify this result, the oil was burned

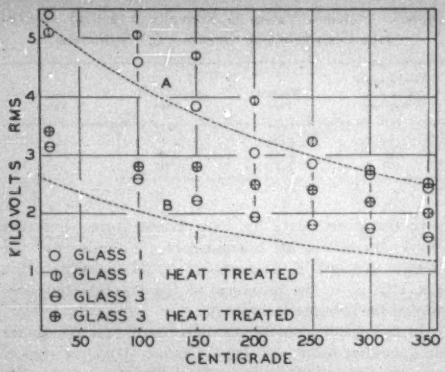

Figure 5. Effect of temperature on a-c breakdown voltage of treated and untreated fibrous glass

A—Glass 1, thickness of layer 1.8 millimeters
B—Glass 3, thickness of layer 0.75 millimeter
Dotted curves are for air gaps

off some samples of glasses 1 and 3, and direct comparisons were made. The heat treatment was completed in two phases: First the glass was heated to 300 degrees centigrade under a reduced pressure of about 15 millimeters of mercury, in order to evaporate the oil to a large extent. Next the glass was heated to 450 degrees centigrade under normal pressure, to burn off any remainder.

The results of a-c tests on these samples are shown in figure 5. The difference between the untreated and heat-treated samples is quite pronounced. The divergence is certainly due to the presence or absence of the oil, as shown by the fact that the difference is pronounced especially between 150 and 200 degrees, that is, in the range in which the oil begins to oxidize. It can be concluded that a removal of the oil from the cloth would certainly improve its quality.

According to our experience the heat treatment, if not performed carefully, is likely to make the glass fibers brittle. The washing process might prove more feasible as an industrial operation.

Leakage Tests

To supplement the foregoing results, a few measurements of the leakage resistance of fibrous glass were made, in following up its variation with temperature.

Because of the minute currents, a d-c amplifier was used, incorporating an electrometer tube in combination with a portable galvanometer. The principle of grid-current compensation was used. The grid resistance was a picric-acid liquid resistor of 600 megohms.[8]

The glass cloth (number 1), ten by ten centimeters in area and 0.5 millimeter thick, was placed between two plane brass plates in an electric oven. The voltage, supplied by dry batteries, varied from 4.5 to 90 volts. The measured total resistance of the cloth was multiplied by the factor 2,000, in order to obtain the resistivity in ohm-centimeters.

Figure 6 shows the result, the Briggs (base ten) logarithm of the leakage resistivity (ρ) being plotted against the reciprocal of the absolute temperature, since this type of plotting is most likely to give straight lines. The lower curve refers to the original cloth, and the upper one to a sample heat-treated according to the process just described. Both cloths were unconditioned.

The untreated cloth was measured from 25 up to 125 degrees centigrade (not further, in order not to burn the oil) and then back. The heat-treated one was measured from 60 up to 160 degrees centigrade and then back (the apparatus was not sensitive enough for this cloth near room temperature). Upward and downward points are sufficiently close, as can be seen.

The essential result of this measurement is the superiority of the heat-treated cloth as compared with the original one, its leakage resistance being one to two orders of magnitude higher. The same result was obtained by having both the untreated and treated cloth dried at 125 degrees centigrade for a few hours previous to the measurements; all resistance values increased from three to ten times, with the difference between the two cloths persisting. It is easy to understand that a thin film of oil on the surface of the fibers will increase the conductivity, partly by facilitating the retention of moisture. Thus, the conclusion stated in the previous section is here confirmed and explained. The higher conductivity of the untreated fibers will shift the field strength ratio between the two components in favor of the air, thus causing a reduction of the breakdown strength.

Apart from this difference it is essential to point out that both cloths have a very high and satisfactory leakage resistance even at higher temperatures, indicating the usefulness of this new material for electrical purposes.

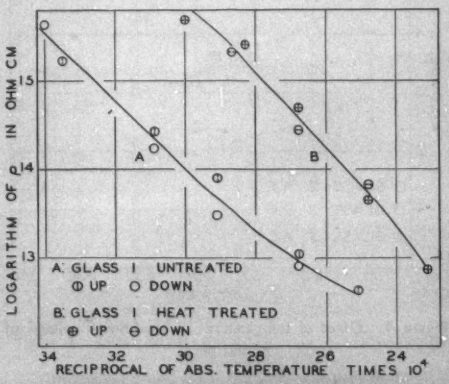

Figure 6. Effect of temperature on leakage resistivity of untreated and heat-treated fibrous glass

Summary

This article presents the results of research into the electric strength of unimpregnated fibrous glass. The chief results are the following:

1. The (maximum) breakdown voltages for alternating current are higher than the corresponding values obtained with direct current.

2. The density of the texture has only little effect on the electric strength. Further increase of the density would be desirable.

3. The electric strength increases linearly with pressure (measured up to five atmospheres) though the values are lower than those corresponding to an air gap of same separation.

4. Measurements up to 350 degrees centigrade indicate satisfactory electric strength even at higher temperatures, although the puncture values decrease with increasing temperature. Heat-treated and washed samples, from which the small proportion of oil is removed prove superior at higher temperatures.

5. The leakage resistance (measured up to 160 degrees centigrade) is very satisfactory (10^{16} to 10^{13} ohm-centimeters) decreasing with increasing temperature in the usual manner, oil-free samples again proving superior to the untreated ones.

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A Bridge for Separating the Components of Traveling Waves

by which the incident, reflected, and standing waves of voltage on a transmission line may be separated for simultaneous and independent measurement

HENRY E. HARTIG
MEMBER AIEE

CLEDO BRUNETTI
NONMEMBER AIEE

THE USE of repeater circuits for amplifying voltage waves traveling in two directions on a telephone transmission line is a routine procedure. The so-called 22-type repeater of the Bell Telephone System accomplishes this by actually picking out the wave traveling in one direction, amplifying it, and then inserting it back into the line in the same direction. The wave traveling in the opposite direction is handled in the same manner without interfering with the action of the first wave.

For purposes of instruction or test it is often desirable to separate the incident and reflected waves on a transmission line and to have a method of measuring separately not only these waves but the total or standing wave of voltage. In the telephone application the wave separation accomplished by the 22-type repeater is merely incidental, the important practical result being the energy amplification. When, however, it is not necessary to amplify but only to examine the wave components separately, the amplification can be eliminated, with a great gain in directness, accuracy, and simplicity. A bridge of the kind to be described has been in successful use for several years in the communication laboratories of the electrical-engineering department at the University of Minnesota and at Lehigh University. It has fixed impedance arms, and when used with the artificial telephone line for which it was designed permits the separation and measurement at a fixed frequency of the incident, reflected, and standing voltage waves at any point on the line and for any line impedance termination.

Consider the Wheatstone bridge in the form of figure 1. All branches are of equal impedance Z_o. If a source of electromotive force is inserted at X, no voltage will appear across BC since the bridge is balanced. The voltages appearing across branches AB, BO, OC, and CA will all be equal. In the same manner, if an electromotive force is introduced at y, the effect across branch BO will be nil. The voltage appearing across BC in this case will be one-half the voltage across AC.

Let us now replace the impedance Z_o in branch AC with a transmission line of characteristic impedance Z_o ter-

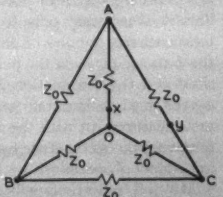

Figure 1. Schematic diagram of Wheatstone bridge

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minated in a load Z_R such that $Z_R = Z_o$ (figure 2). Under such conditions the impedance looking into the line at yy' will be Z_o and the bridge will remain balanced as before. Let the arm AO be replaced by a generator of internal impedance Z_o. Then $E_{BC} = 0$, and $E_{BO} = E_{yy'}$. The voltage $E_{yy'}$ is the incident voltage on the transmission line.

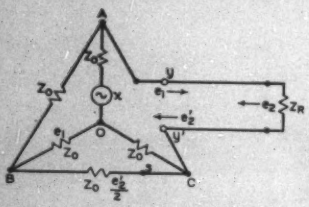


Figure 2. Schematic diagram of resolving bridge

If now the load impedance Z_R be changed from the value Z_o to some other value, the change will produce a reflected wave e_2 traveling back to yy'. The reflected wave arriving at yy' may be considered in place of the actual change in impedance produced there by the change in load impedance Z_R. As explained previously, any voltage appearing at yy' will produce no effect on the branch BO. The voltage across BO, therefore, will remain the same as the incident voltage on the line. The reflected voltage e_2' will appear across the two parallel branches, ABC and AOC. Inspection will show that one-half of the reflected voltage appears across BC. The separation of incident, reflected, and standing voltages, therefore, is accomplished as follows:

$E_{BO} \equiv$ incident voltage, e_1
$2E_{BC} \equiv$ reflected voltage, e_2'
$E_{yy'} \equiv$ standing voltage, $e_1 + e_2'$

If the phase shift along the line is known, the incident and reflected voltages may be combined vectorially to obtain the resultant voltage which then may be checked against $E_{yy'}$. The vector relationship between E_{BO} and E_{BC} may be had by measuring E_{OC} and drawing the voltage triangle. This is, however, not an absolute method. The cathode-ray oscillograph may be used to better advantage in measuring the phase shift between the two voltages.

The problem of obtaining an oscillator or generator of internal impedance of value Z_o is not difficult, since one may add a suitable network to any oscillator to make the impedance looking into the combination equal to Z_o.

If one desires to measure the ratio between the incident and reflected waves of voltage at various points along a line, it is necessary only to connect between yy' and the termination a number of sections of line corresponding to the distance between the point at which the values are desired and the termination Z_R. In this manner one may cover the whole line from generator to load by making the first measurement with the complete line in and gradually removing the sections one by one until only the terminating impedance Z_R remains.

Multiple reflections will not occur since the reflected wave e_2' meets an impedance Z_o upon arriving at yy' and is completely absorbed.

The resolving bridge should prove of value to investigators concerned with studying conditions that cause reflections to occur on transmission lines. Thus a cathode-ray oscillograph connected across branch BC (figure 2) can be used to illustrate only the reflected wave appearing at yy'.

Use of the bridge, however, is not confined to the application just described. Many other possibilities may suggest themselves to the reader. For example, a relay connected in the branch BC (with proper compensation for its impedance) would be actuated only by the return wave, and thus the action of this relay could be controlled entirely by the impedance at the termination of the line. In this manner a sensitive, remote-control device is obtained, especially when used with lines of small attenuation.

Another useful application of the bridge is found upon observing that an impulse originating at X (figure 2) will traverse the line twice before registering at S. Thus a signal at X may be delayed from arriving at S by any desired amount of time by adjustment of the length of the transmission line.

Illumination Notes*

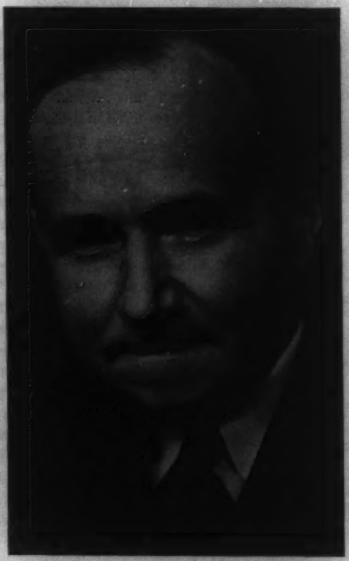
Incandescent-Lamp Ratings. A movement is under way in continental Europe to change the ratings of incandescent lamps from watts to decalumens. The adoption of such ratings would result, when further increases in efficiency are achieved, in giving the customer the same light at lower power cost, instead of more light for the same power cost, as is now the case in the United States under the wattage ratings. Were adequate levels of lighting intensities now generally prevalent, the change in rating would seem logical; but since in fact such levels are still far from attainment in most lighting installations, there would seem to be a strong argument in support of the contention that such change in lamp ratings would be premature.

The Brightest Stadium. The stimulus of the "better light, better sight" campaign is influencing the baseball stadium. The Philadelphia Athletics are playing night games this season under new high intensity levels of floodlighting. Both in the infield, lighted with 135 foot-candles, and in the outfield, with 100 foot-candles, players and spectators may follow the ball with ease. The engineers of the Westinghouse Electric and Manufacturing Company, who designed the installation, estimate that the total amount of light would be sufficient to light a highway from Philadelphia to Cleveland with an intensity corresponding to present standards.

*Contributed for the AIEE committee on production and application of light by L. A. Hawkins (A'03, M'13) executive engineer, research laboratory, General Electric Company, Schenectady, N. Y.

Marion A. Savage—1938 Lamme Medalist

"For able and original work in the development and improvement of mechanical construction and the efficiency of large high-speed turbine alternators"



AWARDED annually to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery," the AIEE Lamme Medal for 1938 was presented during the Institute's recent combined summer and Pacific Coast convention at San Francisco, Calif., to Marion A. Savage (A'21) designing engineer, General Electric Company, Schenectady, N. Y. At the presentation ceremonies Medalist Savage's achievements were reviewed by P. M. Downing (A'98, M'08) first vice-president and general manager, Pacific Gas and Electric Company, San Francisco, Calif., and past vice-president, AIEE. Following Mr. Downing's address, President John C. Parker made the presentation. Because ill health prevented Mr. Savage's attendance, the medal was presented to P. L. Alger (A'17, F'30) staff assistant to engineering vice-president, General Electric Company, Schenectady, N. Y., who received it in behalf of the medalist and read his response. Essentially full text of Mr. Downing's address and of Medalist Savage's response follows on this and the succeeding two pages.

Accomplishments of Medalist Savage

P. M. DOWNING, Member AIEE

Upon the face of the Lamme Medal is inscribed a pungent aphorism: "The engineer views hopefully the hitherto unattainable." This might well have been written to describe the career of Marion A. Savage, medalist for the year 1938, whom we honor today.

Savage is such an engineer. During the 33 years that have passed since he emerged from college to take up his life work he has been driving steadily forward, conquering heights of accomplishment hitherto unattainable. No man could have done what he has done without the ability to "view hopefully," the difficult problems he has tackled and solved.

To him the electrical industry owes a heavy debt for what is so inadequately described in the medal award as "able and original work in the development and improvement of mechanical construction and the efficiency of large, high-speed turbine alternators."

How great that debt may be is as yet not fully determined. The trend toward more general installation of large steam-turbine generating units is definite, even in areas like the Pacific Coast where water power in the past has dominated the generating field because of its low operating cost. It may be that the high-speed turbine alternators developed by Savage and his associates, when operated with cheap fuel, will bring the cost of electric-power production to still lower points than those already reached. The influence of steam generation upon the future of the electric-utility industry can only be surmised at this time. It may indeed prove to be the deterrent that will preserve the integrity of the industry against further encroachments of subsidized publicly owned hydro-electric projects.

Marion A. Savage was born in Walterboro, S. C., in 1885. He attended Clemson College in his native state and, in 1906, was graduated with the degree of bachelor of science in electrical engineering. From the Clemson campus he went directly into the service of the General Electric Company as student engineer. His postgraduate experience covered 2 1/2 years—spent first at Pittsfield, Mass., on transformer tests and then at Schenectady, N. Y., where he built a broad and solid technical foundation in marine equipment, induction and railway motors, generators, turbines, switchboards, train-control equipment, and other apparatus.

With this preliminary training behind him, the young engineer was assigned, in 1909, to the a-c engineering section of the Schenectady works, and there he began the

studies and the intensive labors that year after year have added to his record of accomplishments.

In 1923 he was placed in charge of the turbine generating department of the company and in 1931 was appointed designing engineer of the department. In the same year Mr. Savage received a Coffin Foundation certificate, con-

The AIEE Lamme Medal

ferred, in the language of the award, "in recognition of his outstanding skill as a designer, as notably demonstrated in the design and development of large steam-driven alternators."

Revolutionary advances have been made in the design of large turbogenerators since Mr. Savage took charge of his company's production. Speeds have been increased from 1,200 and 1,800 rpm to 3,600 rpm; maximum rating has been raised from 50,000 kva to 200,000 kva. In 16 years this one engineer has been responsible for the design of 398 turbine generators having a total rating of 12,970,907 kva. Several of the machines produced under his direction had, at the time, greater output rating than any that had ever theretofore been constructed.

The problems met by Savage and his associates during this period of rapid development were not merely of an electrical nature. Their solution involved also refinements and innovations in numerous branches of mechanical engineering and of metallurgy. This list of accomplishments is long. Among them may be mentioned:

Application of the enclosed cooling system to turboalternators, substitution of hydrogen for air as the cooling medium, and numerous devices to increase the efficiency of the cooling system.

A novel hydraulic pressing device used in assembling the spindles and cylinder of large field bodies of turbine generators.

A two-part generator frame design which permits shipment of the inner frame with complete assembly of armature core and winding.

A twisted-lead armature-winding-transposition design which secures low eddy current losses in large armature windings with small numbers of turns.

The development of an end twist in stator windings to equalize the impedance of the different strands in the conductors of the winding.

In co-operation with the metallurgists and steel manufacturers, Savage has brought about improvements in forgings to meet the severe mechanical stresses imposed in high-speed generators.

Other innovations include a new method for stretching metal cylinders, the adaptation of aluminum field windings to 3,600-rpm machines, and grooving of the rotor surface to reduce eddy currents. As an inventor, Mr. Savage is credited with patents covering especially devised flow meters, liquid-filled cooling pads, a design for a two-part generator frame which permits the shipment of a completely assembled turboalternator of much larger size than otherwise would be possible, and many other improvements valuable to the industry.

The foregoing are only a few of the accomplishments of this one engineer. By making available high-speed steam-driven generators of large capacity, he has conferred substantial benefits upon the electric-utility industry and upon all users of electricity. Cost of equipment and of power-station buildings per kilowatt of capacity has been sharply reduced. Vertical compound turbine generators built under his direction have made possible substantial savings in the cost of foundations and buildings.

During his busy life, most of which has been devoted to the heavy responsibilities imposed upon him, Mr. Savage has found time to share the results of his researches with the engineering profession. He has contributed numerous articles to this Institute and, in 1930, presented a paper before the Second World Power Conference at Berlin entitled "Economic Developments in Turbine Generators in the United States."

In thus briefly outlining the career and work of Marion Savage, I cannot refrain from speaking of the unfailing courage and enthusiasm with which he has carried on during recent years, in spite of the heavy handicap of illness. He could not be with us today for this reason, but in his home at Scotia, N. Y., I hope he will sense in some measure, the admiration and the high respect in which he is held by his fellow engineers of this Institute.

He richly merits the award conferred upon him today—not only as an outstanding engineer of distinguished accomplishments, but as a man.

A Good Designer Must Be a Good Prophet

MARION A. SAVAGE, 1938 Lamme Medalist

All engineers who have to design electrical machinery honor the name of Benjamin G. Lamme, who did so much to advance the designing art. It was my good fortune to know Mr. Lamme personally. His kindly nature, remarkable memory, and keen mind were an inspiration to a young engineer. In accepting this medal given in memory of his achievements, I do so not as a personal tribute, but rather as a tribute to a small but loyal group of men who have worked with me in my own company, as well as to those in other companies who have done so much to bring the turbine generator to its present state of development.

There is born in all of us a desire to build something, whether it be a mouse trap or a monolith. It makes no difference to the builder whether the thing he builds becomes the butt for all of the family jokes or not. If he has

labored long and brought forth something, it is a thing of beauty, in which he takes secret pride. In your professional designer this creative desire has been fostered to the point where it becomes a vocation rather than an avocation. His satisfaction in accomplishment is none the less keen. His greatest reward comes when, after laboring over some design for a year or more, and the thing is finally built, he finds that all of its component parts fit together, with none missing and none left over, and that it performs the task for which it was designed.

AIEE Lamme Medalists

1928	Allan B. Field
1929	Rudolph E. Hellmund
1930	William J. Foster
1931	Guiseppi Faccioli
1932	Edward Weston
1933	Lewis B. Stillwell
1934	Henry E. Warren
1935	Vannevar Bush
1936	Frank Conrad
1937	Robert E. Doherty
1938	Marion A. Savage

It has always seemed to me that a good designer must be, more than anything else, a good prophet—that is, he must prophesy not only what it is possible to do in the way of technical performance, but he must predict what his own organization can do in detail, and promise that performance in a given time and with a given amount of money.

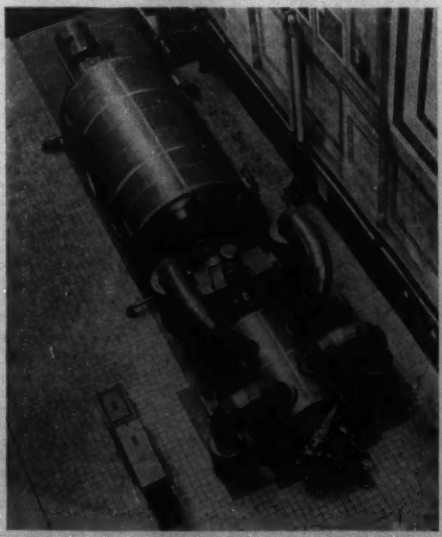
A designer has one advantage over other kinds of prophets, as he deals with materials and natural laws which are definite and will always repeat themselves. In the words of a metallurgist friend, "Steel and copper never lie." It is often difficult to read the message that a piece of metal has to tell you, but you can be sure that whatever it says it will not go back upon. Any who enjoy crossword puzzles will appreciate the pleasure a designer takes in solving the riddles posed by the varied and often unexpected behavior of the materials and structures with which he has to deal. In a large turbine generator of modern design, the variety of these problems is very great, and the opportunities for creative and enjoyable work are correspondingly large.

A designer must also be somewhat of a prophet in predicting the trends in design, and what the public will desire, several years ahead of the actual demand. Quite frequently the ground work on a design may be laid years before the actual building of the machine. This is illustrated in the development of hydrogen cooling for turbogenerators. This form of cooling was first suggested in 1922, and considerable developmental work was done. By the year 1929 so much progress had been made, and we had become so enthusiastic over it, that in a paper before the AIEE Pacific Coast Convention of that year we threw all caution to the winds and made the following prophecy: "Hydrogen cooling is a perfectly practicable thing, and its adoption will mark the next big step forward in the increase in efficiency of these large units." (See "Design Features That Make Large Turbine Generators Possible" by W. J. Foster and M. A. Savage, AIEE TRANSACTIONS, volume 49, 1930, pages 60–7.)

After making this prediction, we sat back and waited for the orders for hydrogen-cooled machines to pour in, but not one was received. Such are the trials of the prophets. It was not until the advent of the large 3,600-rpm units, in which the windage losses comprise a greater proportion of the total losses, that hydrogen cooling was finally adopted; and in 1935 we actually started to build our first hydrogen-cooled machine.

While the designer receives a great deal of pleasure when his prophecies come true, or when he solves some new problem in engineering, the real thrill and sense of satisfaction come from seeing the completed result of his labors put into service. Thus, I am sure you all appreciate the pleasure it has given all of my associates in the design of large generating apparatus to have so many of these new hydrogen-cooled 3,600-rpm generators go into successful service during the last two years. I believe that these machines mark a notable advance in design, making possible more efficient and dependable service of power supply for the entire country.

The acceptance of a national medal involves certain hazards to the recipient. He is supposed to know something. This on occasion might be embarrassing. I am reminded of some advice given us by one of our old professors at college. He was by reputation quite a wit. Being a firm believer in the old adage that "brevity is the soul of wit," he spoke in a rather terse, clipped manner. On the occasion of our last meeting with him, he gave us this gem: "You boys meet with me for the last time this morning. You are about to be graduated and go out into the world. I suppose you think you know it all—but you don't. My advice to you when you get outside is: Don't talk too much. If you do, they will be certain to find out how little you do know. Class is dismissed." After thirty-three years, I still think that is pretty good advice.



The hydrogen-cooled generator of this modern turbine-generator set was designed under the direction of Mr. Savage

News

Of Institute and Related Activities

55th Annual Summer Convention Held in San Francisco, Calif.

COMBINED with the annual Pacific Coast convention, the Institute's 55th annual summer convention, held at the Fairmont Hotel, San Francisco, Calif., June 26–30 inclusive, was the second such meeting to be held by the Institute on the Pacific Coast. Upon three other occasions, summer conventions have been held west of Chicago: Salt Lake City, Utah, 1921; Denver, Colo., 1928; Pasadena, Calif., 1936.

As may be noted from accompanying tabulations, the total registered attendance of 940 at San Francisco was well above the long-time average attendance for summer conventions (815 for the period 1920–38, inclusive). Other details pertaining to convention activities may be found on the following pages.

Annual Business Meeting

Returning to the practice of previous years, the Institute's official annual meeting was the first thing on the program, held the morning of the first day of the Convention rather than the second as at Washington last year. The meeting was called to order at 10 o'clock Monday morning, June 26, in the Gold Ballroom of the Fairmont Hotel by General Convention Chairman S. J. Lisberger. Mr. Lisberger successively introduced Past Vice-President P. M. Downing (1925–27) who delivered an address of welcome; H. W. Hitchcock, vice-president-elect; and President John C. Parker, who presided for the business session.

In his remarks of welcome, Mr. Downing, by way of reminding his audience of the contributions to electrical history made by the Pacific Coast, presented the following comments:

"It is especially appropriate that this year's convention of the Institute be held in San Francisco. It so happens that this year marks the 60th anniversary of the establishment of what we believe was the first central electric generating station in the world's history.

"This was the plant of the California Electric Light Company, one of the progenitors of today's Pacific Gas and Electric Company. It began operating in 1879. The equipment of the station was crude and small. It consisted of two Brush generators, one with a capacity of 5 and the other of 16 arc lamps. The original Palace Hotel was one of the first customers.

"While electricity had been generated prior to 1879 in individual factories and other places for lighting purposes, the San Francisco plant appears to have been the first on record to be established for the commercial distribution of electricity to customers at a distance from the generating machines. History gives the honor to the Pearl Street Station of New York, but there seems to be no doubt that two years or more before Pearl Street started operating, electricity was being delivered to arc lights on the premises of customers in San Francisco.

"Electrical developments followed in rapid succession. The record shows the first of all hydroelectric installations was built in San Bernardino in 1887. The first such plant to serve a distant demand was built at Oregon City in 1889 to supply the city of Portland, Ore., thirteen miles away. The first three-phase installation transmitting a distance of 23 miles at 10,000 volts was the Mill Creek Power House No. 1 installation in southern California. The first such installation in northern California went into operation in 1895, when the 3,000-kilowatt Folsom plant began transmitting power at 11,000 volts over a line 22 miles long to Sacramento. That plant is still in operation as a part of the Pacific Gas and Electric Company's system.

"Tribute is due to the entire electrical engineering profession for the achievements of its members on the Pacific Coast, especially in the fields of hydro construction and generation, long-distance high-voltage transmission and rural electrification."

With this as a background, Mr. Downing mentioned the wealth of sight-seeing and technical inspection trips available in and from San Francisco. Mr. Hitchcock amplified Mr. Downing's latter remarks and, on behalf of other visitors, expressed appreciation to the committees responsible for the excellence of the program arranged. President Parker, in taking over the gavel, likewise paid tribute to convention committees.

Reports of the Board of Directors and the Committee of Tellers

In keeping with custom, National Secretary H. H. Henline presented an abstract of the annual report of the board of directors for the fiscal year ending April 30, 1939, emphasizing that the full text of the report was available to every member (published in ELECTRICAL ENGINEERING, July 1939, pages 305–17, inclusive; also reprint pamphlets). Among the highlights mentioned by Mr. Henline were the following: That two new sections—San Diego, Calif., and Mansfield, Ohio—were formed during the year, bringing the total to 67; that section meeting activities had expanded for the fifth consecutive year, having run from 521 meetings to 635 in that period of time; that the holding of group meetings, special technical meetings, and other special activities intended to broaden the appeal of section activities likewise had expanded; that of the 120 Student Branches, only one failed to report activities during the past year; that the publication committee with the approval of the board of directors had put into effect a revised publication policy during the year; and that membership during the year increased from 16,078 to 16,605, representing about 90.5 per cent of the maximum peak as against the level of about 78 per cent to which it fell during the depth of the depression.

Section and Branch activities, mentioned only in abstract by Mr. Henline and in the report of the board of directors, are reported in detail in the comprehensive annual report which may be found on pages 268–71 of the June issue of ELECTRICAL ENGINEERING. Other items concerning Section and Branch activities have been published throughout the year, as they have become available.

As a traditional part of the annual meeting program, the names of the newly elected officers were read, and President Parker presented to President-Elect Farmer his official badge of office. The text of the report of the committee of tellers was published on page 301 of the July issue. The texts of President Parker's convention address and of Mr. Farmer's initial message as president may be found elsewhere in this issue.

Treasurer's Report

Verifying the record of the Institute's finances, as published by the auditor's statement included in the report of the board of directors, National Treasurer W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y., gave a digest reflecting the Institute's financial position. Although income was down slightly for the year ended April 30, expenses were reduced accordingly, thus for the fourth successive year enabling the placing of a nominal amount in the reserve capital account against future possible requirements. Based upon the cost of securities in this fund, Treasurer Slichter reported an average rate of 4.11 per cent income for the year 1938–39. He reported also various changes in investments, with a trend toward high-grade and short-term bonds in the interests of greater security and greater liquidity.

Prize Awards

Chairman H. S. Osborne of the committee on award of Institute prizes read a report covering the awards made for technical papers presented during 1938. This report was published in full on page 271 of the June issue.

AIEE Lamme Medal for 1938 Presented to M. A. Savage

"For able and original work in the development and improvement of mechanical construction and the efficiency of large high-speed turbine alternators," the eleventh AIEE Lamme Gold Medal was presented to Marion A. Savage (A'21), designing engineer, General Electric Company, Schenectady, New York. Ill health prevented the attendance of Mr. Savage. Consequently it was to P. L. Alger of Schenectady, representing Mr. Savage, that President Parker presented the medal and the certificate. Preceding the award presentation, Director D. C. Prince of Philadelphia gave a brief discussion of Benjamin Garver Lamme and the medal, and Past-Vice-President P. M. Downing of San Francisco outlined the career of the medalist. On behalf of the medalist, Mr. Alger read a message from Mr. Savage. The text of the statements by Mr. Downing and Mr. Savage may be found elsewhere in this issue.

Established for the encouragement and recognition of "meritorious achievements in the development of electrical apparatus or machinery," the AIEE Lamme Medal is one of three such bequests provided in 1924 in the will of Benjamin Garver Lamme, former chief engineer of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., who died July 8, 1924. The bequest provides for the award by the Institute of a gold medal, together with a bronze replica thereof, annually to a member of the AIEE, and for the award of two such medals if in some years the accumulation from the fund warrants such action. A committee composed of nine Institute members makes the award.

Other Lamme Medal Awards

One of the other bequests was made to the Society for the Promotion of Engineering Education, "for accomplishment in technical teaching, or actual advancement of the art of technical training," which award for 1938 (the twelfth) went to Doctor Steven P. Timoshenko, professor of mechanics, Stanford University, California. The third bequest was made to Ohio State University, Columbus, "for meritorious achievement in engineering or the technical arts," which current medal was awarded to Thomas A. Boyd of the General Motors Research Laboratory.

Other Convention Features

With only minor exceptions the technical and general sessions and entertainment features of the convention followed the pattern of the program as previously published in Electrical Engineering. The 41 technical papers, presented during the course of the 9 technical sessions, will be published in volume 59 (1940) of the annual Transactions, and certain of them will be scheduled for reprinting in the Transactions sections of the early 1940 issues of Electrical Engineering. The general session address, "Human Relationships," given by Dr. Adam S. Bennion, assistant to the president of the Utah Power and Light Company, is scheduled for publication in an early issue.

Two informal technical conferences—one on the subject "Teaching of Communication and Electronics," and one on the subject "Sensitive Ground Protection"—were the scenes of active discussions by the two groups interested in these special topics. The sessions were not reported.

The convention meeting of the Institute's board of directors is reported elsewhere in these columns.

Student Activities

Two student technical sessions were held on Wednesday and Thursday afternoons to avoid conflict with other technical sessions:

Wednesday Afternoon, June 28

Presiding, Cecil Carrière, University of California.

Transient Response of Crystal Microphones, **Paul Engelder, California Institute of Technology**

Water-Cooled Radio Frequency Amplifiers with Grounded Anodes, **Opal Cummins and Willice E. Groves, University of Utah**

The Construction of Low-Grid-Loss Receiving Tubes, **E. N. Proctor, Stanford University**

Measurements of Galvanic Reactions, **Joseph B. Possner, University of Southern California**

Generation of Square-Wave Voltages at High Frequencies, **W. H. Fenn, University of California**

Thursday Afternoon, June 29

Presiding, M. F. Fraresso, University of British Columbia

Investigation of a Network Relay as an Automatic Synchronizing Device, by Student Branch Chairman, University of Nevada

Compound Frequency Control of Power Systems, **Thomas E. Curtis, University of California**

Transient Stability of Synchronous Machines, **M. H. Yamakawa, Stanford University**

A Survey of the Electric Power System of the Cornucopia Gold Mines, **Louis N. Stone, Oregon State College**

Dynamic Characteristics of D-C Single-Operator Arc Welders, **Joseph S. Mascovich, University of Santa Clara**

A New Design AC-DC Meter, **Keats Pullen, California Institute of Technology**

A Student Branch dinner was held in the Army and Navy clubrooms of the Fairmont Hotel, Wednesday evening, June 28. The 63 persons attending this dinner included student chairmen and counselors of Districts 8 and 9 and the western portion of District 10, and others interested in Student Branch work. Following the dinner meeting, a conference session was held under the chairmanship of Professor W. G. Angermann of the University of Southern California, Los Angeles, chairman of the committee on student activities for District 8. The principal portion of this session was devoted to informal addresses, delivered by President Parker, Vice-President-Elect H. W. Hitchcock, and Chairman R. W. Sorensen of the national committee on Student Branches.

Entertainment

The three principal features of the organized entertainment program were the tea for men and women held Monday afternoon in the Mark Hopkins Hotel; the "AIEE Day" at the Golden Gate International Exposition on Treasure Island, which culminated in a convention dinner held at the Yerba Buena Club on the Island, with a heavy overflow accommodated at the nearby Island Club; and the convention banquet with its entertainment and dancing held Thursday evening in the Gold Ballroom of the Fairmont Hotel. Attendance at the various activities, as reported by the committee in charge, was as follows:

	Number Participating
Sight-seeing Tour of San Francisco, Monday afternoon, June 26	225
Women's trip to Stanford University and luncheon at Allied Arts, Thursday, June 29	75
Men's trip to Stanford University and Ryan Laboratory, Thursday afternoon, June 29	100
Men's trip to University of California and Cyclotron, Friday afternoon, June 30	60
Trips to points of interest of the San Francisco-Oakland Bay Bridge Electrification Project	80
Miscellaneous trips to Stations A and C, Marten Station, etc.	50
Informal reception and Tea at Hotel Mark Hopkins, Monday afternoon, June 26	487
Dinner on Treasure Island, Yerba Buena and Island Clubs, Tuesday evening, June 27	500
Banquet at Fairmont Hotel, Thursday evening, June 30	474

Sports Events

With weather conditions ideal for comfortable attendance at the various technical sessions and other meetings, and with the severe competition offered by the Exposition and the many scenic and historical attractions of the city of San Francisco, the several traditional sports competitions suffered rather severely for lack of contestants. Effective work on the part of the

Table I. Analysis of Attendance at 1939 Summer and Pacific Coast Convention, San Francisco, Calif.

Classification	Districts										Totals
	1	2	3	4	5	6	7	8	9	10	
Members	30	35	32	13	31	7	15	254	54	7	478
Enrolled Students						1		39	16	1	57
Men guests	7		3		11	1	3	34	15	1	75
Women guests	12	28	22	9	27	6	13	155	53	5	330
Totals	42	70	57	22	69	15	31	482	138	14	940

Table II. Summer Convention Attendance During Recent Years

1939	San Francisco, Calif.	*(8)	940
1938	Washington, D. C.	(2)	825
1937	Milwaukee, Wis.	(5)	1,067
1936	Pasadena, Calif.	(8)	715
1935	Ithaca, N. Y.	(1)	904
1934	Hot Springs, Va.	(4)	351
1933	Chicago, Ill.	(5)	968
1932	Cleveland, Ohio	(2)	1,022
1931	Asheville, N. C.	(4)	525
1930	Toronto, Ont., Canada	(10)	1,110

* District numbers in parentheses.

committee, however, kept the competitions open, with the following results:

The Mershon golf trophy, available for national competition among Institute members on the basis of match play and handicap, was won by F. R. George of the San Francisco Section, 1/2 up, with W. G. Stearns of San Francisco as runner-up. Mr. George thus becomes the fourth to have his name engraved upon the present trophy, which is the third cup donated by Past-President Ralph Mershon. This trophy remains on display at Institute headquarters.

The Lee trophy, presented in 1932 by the late Past-President W. S. Lee, is awarded each year to the member having the lowest net score for 36 holes, and must be won twice by the same player for permanent possession. Again the principal competition was between two San Franciscans, W. G. B. Euler (handicap 21) winning with a net 135 from D. D. Smalley (handicap 17) whose net score was 139. Mr. Euler thus became the eighth person to win a leg on the cup and the privilege of having his name engraved thereon.

The John B. Fisken golf trophy, placed in competition in 1920 by the Portland Section and named in honor of John B. Fisken (A'03, F'13) of Spokane, Wash., was won by L. J. Moore of San Francisco, with 66 net (handicap 24) against W. G. B. Euler and his 66 net (handicap 21) by a draw. Competition for the Fisken trophy is on the basis of medal play with handicap, and is limited strictly to active members of Pacific Coast Sections.

Guest competition in the golf tournament was won hands down by Frank J. English of Denver, Colo., with 69 net (no handicap).

Professor L. A. Pipes of Cambridge, Mass., won the men's singles in the tennis tournament (3–6, 6–4, 6–3) and thus became the fifth to have his name engraved upon the present Mershon tennis trophy, which was donated in 1935 by Past-President Mershon; runner-up was A. J. Hoover of Denver, Colorado. Honors in the men's doubles were won by F. J. Groat of New York and F. S. Benson of San Francisco (7–5, 6–3) against J. S. Moulton and his son, James, Jr., of San Francisco. The mixed doubles tournament was won by L. A. Pipes of Cambridge, Massachusetts, and Elinore Bricca of San Francisco (6–4, 6–3) against Mr. and Mrs. F. J. Groat of New York. Women's singles tennis tournament was won by Mrs. F. J. Groat of New York, with Mrs. W. C. Lynch of Los Angeles as runner-up.

Aside from the official trophies, the principal items among the valuable prizes distributed by the local sports committee were in the form of merchandise orders, which gave the winners the opportunity to choose awards to suit their tastes.

Tennis matches were played on the courts of the California Tennis Club, San Francisco. Golf tournaments were played at the Claremont Country Club, Oakland, across the bay from San Francisco.

Annual Conference of Officers, Delegates, and Members, Held at San Francisco, Calif.

TWO afternoons, Monday, June 26, and Wednesday, June 28, during the summer convention week in San Francisco were devoted to the sessions of the annual conference of officers, delegates, and members. The conference was held under the joint sponsorship of the AIEE committees on Sections and Student Branches. Attendance at these sessions averaged about 125 and included delegates from 65 of the Institute's 67 Sections, 5 of the 10 District secretaries, counselor delegates from all 9 Districts in which committees on student activities have been organized, and many others interested in this phase of Institute activities. The San Antonio and Mexico Sections were the only ones not represented. With Doctor H. H. Race of Schenectady, chairman of the Sections committee, presiding, the program for these sessions was as follows:

Monday Afternoon, June 26, 2:00 p.m.

Opening remarks—President J. C. Parker

Report on meeting of Sections committee held in New York, January 24, 1939—M. S. Coover

On information to secondary schools—R. W. Sorensen, chairman committee on Student Branches

Short recess to permit Student Branch Counselors to retire to their own meeting.

Section Activities

1. General summary—H. H. Race, chairman Sections committee
2. A "Committee on Young Men" proposed for each Section—Charles F. Scott
3. Potentialities of groups within the Sections—A. L. Powell, chairman New York
4. General discussion of Section activities.

Wednesday Afternoon, June 28, 2:00 p.m.

Changes in assigned territories—H. H. Race, chairman Sections committee

The licensing of professional engineers

1. The Model Law—C. R. Beardsley
2. Experiences with registration problems—Henry D. Dewell, president California State Board of Registrations for Civil Engineers
3. Professional organization of engineers—H. J. Dible, Ohio; I. B. Garthurs, Minnesota; and George Charlesworth, Iowa

Miscellaneous Section problems

At the completion of the first three items on the first session's program, the conference was separated into two groups, the Sections delegates and the Student Branch counselors holding separate sessions.

"Young Men in the Profession"

Ways and means whereby the Institute may serve more effectively the young men of the profession were the subject of appreciable discussion. President Parker, in his brief preliminary remarks, stated that the problem as to what the Institute could do "to make itself more useful to the younger members" was one of the most important that had come to his attention during his presidential year. He pointed out that in some Sections there seemd to be "a very well-developed spirit of making use of the younger men, those in their twenties and early thirties," but that this was "not anywhere near as universal as it should be." In general he urged the Sections to keep the age level of their officers and operating committees down rather than up. He urged that Section and other Institute activities be so arranged as to give the younger members of the profession every possible opportunity to meet with older practicing engineers on grounds of common interest, warning at the same time against any tendency to segregate and isolate the younger members as a class. He urged more effort generally in following the successful lead of certain Sections in "breaking down the age barriers and letting the youngsters feel that this is their Institute and that they have a place in it; that they not only are welcome, but are expected to participate in the activities."

Similarly, Past-President (1902–1903) Charles F. Scott in a written message read by M. S. Coover, concerned himself with the young men of the profession, putting the question, "How can his professional society contribute to his development?" Doctor Scott stated that "'The advancement of theory and of practice' in the future really rests with the young engineers today." He urged that "in each Section a committee of sympathetic, understanding, and alert members join with energetic youth to make a general survey to find the answer." He mentioned as "good but meager" the occasional meetings held by Sections jointly with nearby Student Branches, the various technical and other courses that are being run for the younger engineers by some Sections, and other similar activities. Doctor Scott stated further: "The problem of the young engineer is to be fitting himself for his next and larger job, while concentrating on his present task—it is the challenge of the engineers of today to make better engineers for tomorrow," and urged all Section officers to take the general question seriously to heart. It may be remembered that it was Doctor Scott who, during his term as president, developed the AIEE Student Branch idea and was responsible for broadening the Institute's activities in that and other related directions.

Doctor R. W. Sorensen, chairman of AIEE committee on Student Branches, reported that one of the principal projects of his committee during the past year has been the preparation of new copy for the reissuance of a booklet describing electrical engineering as a profession. The re-issuance of this student guidance booklet was discussed and acted upon favorably at a previous annual conference, and the project subsequently approved by the board of directors. Doctor Sorensen reported that it was the hope of his committee to be able to have the booklet in circulation by the beginning of the forthcoming school year, and that it would serve as the basis for effective counseling and guidance for pre-college students interested in electrical engineering. Further on the subject of student guidance, Doctor Sorensen said that he hoped that engineering educators would be able successfully to impress their engineering students with the fact that they should not wait until graduation to be engineers, but that in effect they are engineers when they embark upon a college engineering course. A student with this thought constantly in mind can "direct his course accordingly, instead of planning for something he is going to do after graduation, because, after all, four of the richest years of any student's life are those four years of undergraduate work."

Many Sections reported that the younger men (say under 35 years of age) conduct most of the work of the Section. One Section has 60 per cent of its membership active in committee work.

The chairman urged each Section membership committee actively to seek contact with all student members who move into its territory each year, and to stimulate transfer to Associate grade and participation in Section committee work.

Some of the Sections are now providing information to secondary-school counselors and students to help the latter decide whether they are fitted for and want to subject themselves to the rigorous training required to enter the electrical-engineering profession. *Whether it be through affiliated local engineering societies or through special committees, each Section was urged to consider this activity one of its most important opportunities for service to future members of our profession.*

Section Activities

Section activities came in for liberal discussion and rather extensive exchange of experiences. Chairman Race initiated the discussion of this subject by distributing to the Section delegates, and subsequently abstracting, an eight-page mimeographed report summarizing the information on Section activities that has been accumulated during the last few years by the Sections committee. The underlying purpose of the report was to place in the hands of each new incoming group of Section officers a brief record of the experience that preceding groups of Section officers had found valuable. Abstracts from this report will appear in a later issue of Electrical Engineering.

Chairman A. L. Powell of the New York Section explained at some length the scope and character of the meetings, educational courses, and other special activities that have been conducted by the New York Section during recent years, and which have been effective in greatly increasing the number of individual members participating in the activities of that Section. Liberal discussion and exchange of experiences and views ensued.

Brief discussion indicated that in general the present assignments of Section territory are satisfactory. In response to inquiries, Chairman Race emphasized the fact that any particular point still requiring attention should be taken up directly with the vice-president for the District by the individual or the Section involved, sending copies of correspondence to the chairman of the Sections committee.

Engineering Registration —Proposed Model Law

Initiating a general discussion of the subject of engineering registration and of the proposed AIEE Model Law, Chairman C. R. Beardsley of the AIEE special committee on Model Law reviewed briefly the circumstances that led to the inception of legal registration for engineers, and outlined the history of the movement. Mr. Beardsley reported in part as follows:

"Forty-two states have licensing laws, and others are considering enactments, varying in scope of application and basic requirements. Recently, through efforts of the National Council of State Boards of Engineering Examiners, there is an approach to uniformity and reciprocity. However, there is a great deal of ground to be covered before complete reciprocity will be obtained.

"There has been some misunderstanding of the relation of AIEE to registration. While the Institute has been represented on joint committees in the preparation of other model laws, it has *never* given endorsement to those model laws because they did not fit electrical-engineering practice. Some publications have listed the Institute as having participated, thereby implying endorsement contrary to fact. The AIEE as a group has not taken a position either for or against licensing as a principle. However, in 1937, following some informal meetings and discussion, the board appointed a committee on Model Law. That committee prepared a statement of principles that may be found in the June 1, 1939, draft of the Model Law. The board unanimously approved this statement of principles. The text of the Model Law, based on these principles, was then drafted and circulated to Sections and others in mimeograph form. At Section meetings, it was requested that discussions be held and comment or criticism sent in. A few Sections have complied, mainly those in states contemplating new legislation. Other institutions and state boards have examined the draft. Generally, comment has been favorable. Only a very few adverse criticisms have been received....

"The essential point in controversy is whether or not *all* engineers should be licensed or whether there should be some exemptions. Those who advocate universal licensing do so with the avowed aim of either (1) arbitrarily restricting the number of persons who may practice engineering, thereby limiting supply and raising compensation, or (2) unifying the profession by regimentation in a body authorized by law as the exclusive group who may practice....

"We have taken the position that licensing laws are enactable only for the purpose of protecting the public, and that their scope should be limited to that objective; that laws designed to advance the profession as a group are not only unethical, but unnecessary....

"The remaining differences between the AIEE Model Law draft and others are all corollary to this main question of scope. There are other problems, such as definition of professional engineering and exemptions, level of minimum competence, method and scope of examination (to allow for specialization in various branches of practice), enforcement, reciprocity, maintenance of high integrity in State Boards, etc....

"The Sections are the logical agencies to study legislation and crystallize the opinion of individuals, and to join with other engineering groups actively to oppose or support legislation according to its merit. We can no longer remain passive and lethargic in a matter so greatly affecting engineering futures.

"The Model Law has been sent to various organizations, as well as to AIEE Sections. Already we have the endorsement of some engineering bodies, but most encouraging is the fact that four of the State Boards have endorsed our proposals. Doctor Charles F. Scott, president of the National Council of State Boards of Engineering Examiners, said it has solved for them some troublesome problems....

Section Delegate Flies Own Airplane to Convention

SHOWN here are E. J. Biegel (A'25, M'31) and his airplane, which he flew to the recent summer and Pacific Coast convention, San Francisco, Calif., as the official delegate from the Institute's Memphis Section. The airplane is a low-wing Aeronca and has a cruising speed of about 110 miles per hour. Mr. Biegel says that he flew from Memphis to San Francisco in about 20 hours. He also flew this airplane to the 1938 Pacific Coast convention, held at Portland, Ore., and to the Southern District meeting in Miami, Fla., the end of November, 1938.

Future AIEE Meetings

Great Lakes District Meeting
Minneapolis, Minn., September 27–29, 1939

Middle Eastern District Meeting
Scranton, Pa., October 11–13, 1939

Winter Convention
New York, N. Y., January 22–26, 1940

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Vancouver, B. C., August 27–30, 1940

"We hope to have endorsement or constructive criticism to the effect that all engineering societies can agree on a model law; then gradually, through the local Sections, have it enacted on the statutes of the various states."

President Henry D. Dewell of the California State Board of Registration for Civil Engineers described briefly the highlights of California's experience with ten years of partial engineering registration. Chairman A. L. Powell of the New York Section outlined some of the experiences of the New York Section in connection with the New York State Engineering Registration Laws. Experiences incidental to the organization of engineers in the States of Ohio, Minnesota, and Iowa were described, respectively, by H. J. Dible of the Cleveland Section, I. B. Garthus of the Minnesota Section and George Charlesworth, chairman of the Iowa Section. Subsequent general discussion led to a request from Chairman Beardsley of the AIEE Model Law committee and Chairman Race of the Sections committee that *each Section appoint a special committee, not only to give consideration to the proposed AIEE Model Law, but also to keep constantly in touch with matters of legislation likely to affect electrical engineers.*

Change in Prize Paper Rules

A suggestion originating with the executive committee of the Northeastern District, upon which favorable action was taken by the committee on Student Branches in its San Francisco conference session, resulted in the unanimous adoption of a recommendation to the board of directors that the rule governing the award of District prizes for papers be reworded to read as follows (proposed changes appear in italics):

"Only papers presented *subsequent to those considered for the last previous award in the class, and prior to the end of the last* calendar year shall be considered for the prize for Best Paper and for Initial Paper. Only papers presented *subsequent to those considered for the last previous award in the class and prior to the end of the last* academic (college) year, July 1 to June 30, inclusive, shall be considered for the prize for Branch Paper and for Graduate Student Paper. They must be submitted in duplicate by authors, or by officers of the Section, Branch, or District concerned to the District secretary on or before the following dates: Best Paper and Initial Paper—February 15; Branch Paper and Graduate Student Paper—July 15."

The purpose of this proposed change in rules is to enable papers submitted for prize competition to be accumulated for more than the present stipulated one-year period. This point is of especial significance where perhaps only one or two papers become available in any one year.

Counselor-Delegate Session

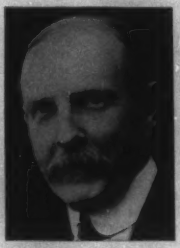
After a preliminary period of joint session with the Section delegates, the counselor-delegates and others especially interested in the work of the committee on Student Branches withdrew from the general conference Monday afternoon, June 26, to hold a separate session under the direction of Chairman R. W. Sorensen of that committee. Incidental to the discussion of problems and questions of mutual interest, two recommendations were adopted:

1. That the "rules governing the award of Student Branch papers be so amended that each District be permitted to set the closing date for papers from that District to be considered for the District Student Branch paper award."

2. That the "committee on Student Branches be encouraged to give consideration to other than monetary awards for District prize-winning papers."

The substance of the first recommendation subsequently was endorsed by the conference as a whole, which adopted a recommended re-wording for the District prize regulation, as reported in a preceding paragraph. The second recommendation was referred to committee for consideration.

In Memoriam



ARTHUR E. KENNELLY

ON THE 18th day of June, 1939, a man pre-eminent on the honor roll of the Institute's great passed from our ranks. In the loss of Doctor Arthur E. Kennelly, there was taken from us one of those few of whom it can be truly said neither his word nor his motives were ever questioned. Universally recognized for his ability to solve the most intricate of technical problems, it was, however, through his frequent and unanimous selection as the presiding judge in the bitter debates through which the profession of electrical engineering has come that there was placed upon Dr. Kennelly the real hallmark of his qualities as a man.

Born in 1861, Doctor Kennelly received his education in the schools of Europe and America. At the age of fourteen, he became assistant secretary of what is now the Institution of Electrical Engineers. Employed in his early days in the telegraph field, he became in 1887 the principal assistant to Thomas A. Edison. Later he was consultant for the Edison General Electric and the General Electric Company. In 1902, he was appointed professor of electrical engineering at Harvard, becoming professor emeritus at that University and the Massachusetts Institute of Technology in 1930. A prolific writer, Doctor Kennelly's best known contribution probably is his explanation of the mechanism of the transmission of radio waves.

The recipient of degrees and honors both here and abroad, Doctor Kennelly was named Honorary President of the International Electrotechnical Commission. He was a member of many of the most important of our Institute committees and served as manager, vice-president, and finally president for the terms 1898 to 1900. In 1933, he was elected an Honorary Member and in the same year was awarded the Edison Medal.

With this brief outline of the accomplishments of Doctor Arthur E. Kennelly, it is with the keenest appreciation of the many parts he has ably played in the life of the Institute and the profession that the board of directors hereby expresses its deep sorrow at his death, and resolves that this minute be spread on the Institute records.

—AIEE Board of Directors, June 27, 1939

Board of Directors Approves Model Registration Law

In view of the endorsements and many favorable comments received, the AIEE board of directors at its meeting in San Francisco, Thursday, June 29, 1939, voted unanimous approval of the June 1, 1939 draft of the AIEE Model Law, proposed for governing the licensing of engineers. A communication from Chairman C. R. Beardsley of the special AIEE committee on Model Law, addressed to all the AIEE Sections, supplements the general discussion that took place on the subject at the annual conference of officers, delegates, and members, held during the summer convention in San Francisco and reported elsewhere in these columns. Mr. Beardsley pointed out that in October 1938 the Institute's board of directors had authorized the issuance and preliminary distribution of this draft as tentative and for the purpose of obtaining comments that would have a bearing upon modification or adoption of the draft. Generally favorable comment has been received from both within and without the membership of the Institute, including favorable comments from several State Boards of engineering registration.

As to the possible applications of the Model Law, Chairman Beardsley pointed out that the "Sections are, of course, autonomous as to their consideration of local problems, and the national body and officers are estopped from intervention in such matters. It hardly needs the suggestion that Section action should not be such as to involve the national body by the inference that it—rather than the Section—is the author of any local action or statement." Mr. Beardsley urged that all Sections that have not already done so should appoint committees on legislation, so as to keep continuously in touch with matters of local and State legislation likely to affect the status of electrical engineers,

pointing out that members of Sections may wish to oppose or support amendments according to their judgment of the merit of individual proposals. It is emphasized that such laws may have a far-reaching effect on engineering practice and progress, and that engineers cannot afford to be passive and unwary. Such committees may well compare any proposed amendments with the AIEE Model Law, which has received a preponderance of endorsement as being well suited to the control of the practice of electrical engineering.

Chairman Beardsley emphasized the fact that the June 1 draft of the Model Law is considered neither perfect nor final; that the special committee and the board are anxious to give attention to any suggestions for possible improvement that may arise incidental to local conditions that may be encountered by any Section. He asserted that, with licensing laws now existing in forty-two States, and probably soon to exist in the remaining States, "all considerations should look toward complete reciprocity." As evidence of the importance of this point, Chairman Beardsley cited the case of the chief engineer of a large holding company who was obliged to undergo the routine of application and examination in several States in order to conduct his work therein.

The committee on Model Law is cited as standing ready to analyze and advise in any way in which any Section may desire assistance. Inquiries or comments may be addressed either to National Secretary H. H. Henline or to Chairman C. R. Beardsley of the AIEE special committee on Model Law, 4 Irving Place, New York, N. Y.

Three Districts Announce Prize Awards for Papers

District prizes for AIEE papers have been announced by three Districts to date. Other District prizes will be announced later as the information becomes available. The awards are for papers presented during 1938, except Branch papers, which must have been presented during the academic year ending June 30, 1938, according to the revised rules adopted in 1937.

DISTRICT 1

Prize for best paper was awarded to C. W. LaPierre and A. P. Mansfield for their paper "Photoelectric Weft-Straightener Control," presented at the North Eastern District meeting, Lenox, Mass., May 18, 1938.

Prize for Branch paper was awarded jointly to Edward G. Schroeder for his paper "Investigation of Heat Dissipation and Temperature Rises in Underground Ducts" and to P. P. Koliss and Joseph Ezen for their paper "Analysis of an Electron-Tube-Controlled Induction Motor," presented at the North Eastern District meeting, Lenox, Mass., May 20, 1938.

DISTRICT 2

Prize for Branch paper was awarded to Joseph M. Rodgers for his paper "An Automatic Frequency Regulator for D-C Motor-Driven Alternators," presented at a joint meeting of the Cincinnati Section and University of Cincinnati Branch, May 12, 1938.

DISTRICT 9

Prize for best paper was awarded to Edgar C. Goodale for his paper "A Graphical Method of Multiplying and Dividing Complex Quantities, and Its Use in the Solution of Impedance Networks," presented at a meeting of the Seattle Section, March 22, 1938.

AIEE Directors Meet During Summer Convention

THE regular meeting of the board of directors of the American Institute of Electrical Engineers was held at the Fairmont Hotel, San Francisco, Calif., June 29, 1939, during the annual summer convention of the Institute.

Present: *President*—John C. Parker, New York, N. Y. *Past President*—A. M. MacCutcheon, Cleveland, Ohio. *Vice-Presidents*—F. C. Bolton, College Station, Tex.; C. L. Dawes, Cambridge, Mass.; F. M. Farmer, New York, N. Y.; L. R. Gamble, Spokane, Wash.; J. P. Jollyman, San Francisco, Calif.; I. M. Stein, Philadelphia, Pa.; E. D. Wood, Louisville, Ky. *Directors*—C. R. Beardsley, H. S. Osborne, New York, N. Y.; W. B. Kouwenhoven, Baltimore, Md.; F. H. Lane, L. R. Mapes, Chicago, Ill.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa.; D. C. Prince, Philadelphia, Pa.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y. Present by invitation: Vice-President-Elect H. W. Hitchcock, Los Angeles, Calif.

Minutes of the meeting of the board of directors held May 26, 1939, were approved.

The board adopted a resolution in memory of Doctor Arthur E. Kennelly, past-president, Edison Medalist, and Honorary Member of the Institute, who died on June 18, 1939. (See preceding page.)

A report was presented and approved of a meeting of the board of examiners held on June 15, 1939. Upon the recommendation of the board of examiners, the following actions were taken: 4 applicants were transferred to the grade of Fellow; 22 applicants were transferred and 10 were elected to the grade of Member; 120 applicants were elected to the grade of Associate; 46 Students were enrolled.

The finance committee reported expenditures in June amounting to $22,952.04, and the report was approved.

Dates of August 27–30, recommended by the local officers concerned, were approved for the 1940 Pacific Coast convention to be held in Vancouver, B. C.

Upon request of the Baltimore Section and recommendation of the Sections committee, the board authorized a change in name of that Section to "Maryland Section."

Having been elected to the presidency of the Institute for the year beginning August 1, 1939, F. Malcolm Farmer tendered his resignation as vice-president, representing the New York City District, as of July 31, 1939. His resignation was accepted by the board.

Upon nomination of the executive committee of the New York City District, the board elected T. F. Barton vice-president of the Institute, New York City District (number 3) for the unexpired term, ending July 31, 1940, of Mr. Farmer.

The resignation of Gano Dunn as a representative of the Institute on the Hoover Medal Board of Award was accepted, and Past-President A. W. Berresford was appointed for Doctor Dunn's unexpired term, ending in May 1945.

The board voted unanimously to approve the June 1, 1939, AIEE Draft of Model Law for Registration of Professional Engineers and Land Surveyors, which had been prepared by a special committee of the Institute and discussed at this and previous meetings of the board of directors, distributed to the Sections of the AIEE, and discussed at the conference of officers, delegates, and members held June 28, 1939.

R. W. Sorensen was appointed a delegate of the Institute to attend the annual meeting of the National Council of State Boards of Engineering Examiners, July 26–29, 1939, in San Francisco, Calif.

The board adopted resolutions expressing appreciation of the effective services of the 1939 combined summer and Pacific Coast convention committee and its subcommittees, and of the women's entertainment committee.

The meeting adjourned after an expression by President Parker of his appreciation of the co-operation given him by the members of the board during his term as president, followed by a rising vote of thanks to President Parker for his faithful and effective administration.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Executive Committee of Southern District Meets

During the recent AIEE combined summer and Pacific Coast convention at San Francisco, Calif., a luncheon meeting of delegates from the Institute's Southern District (4) was held June 28. Those present were:

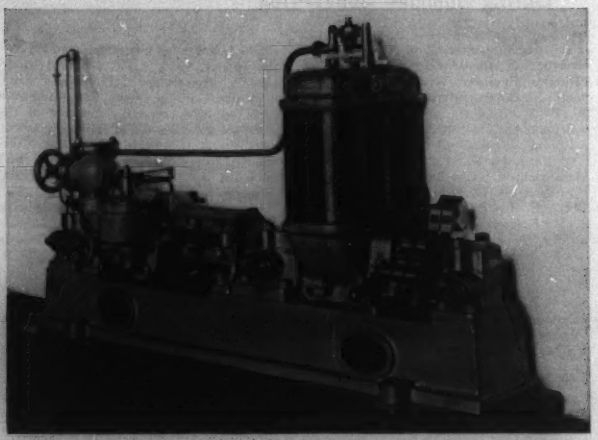
E. D. Wood, vice-president, Southern District
L. L. Patterson, District student counselor delegate
R. S. Fouraker, North Carolina Section
F. R. Maxwell, Jr., Alabama Section
J. M. Flanigen, Georgia Section
E. J. Biegel, Memphis Section
F. B. Bell, Muscle Shoals Section
L. L. Newman, New Orleans Section
J. F. Housley, East Tennessee Section
E. F. Smith, Florida Section
A. S. Hoefflin, district secretary, Louisville Section

Following approval of the minutes of the last meeting of the committee, Vice-President Wood, who presided, expressed his gratification that delegates from all Sections in the Southern District were present at the convention and that all were present at this meeting, except one—J. A. Rawls of the Virginia Section.

Mr. Flanigen reported that the Georgia Section is proposing that the 1941 AIEE summer convention be held in Atlanta, and urged all Section representatives to back the proposal in every way possible. It was understood that if the invitation is accepted by the national board of directors, no meeting will be held by the District prior to that time.

The question of whether or not Institute Section meetings should be open to the

Early Parsons Steam Turbine at New York Fair



AN engineering relic of unusual historical interest is the Parsons reaction-type turbo-generator unit, built in 1885, now on exhibition in the Hall of Metals of the British Government Pavilion at the New York World's Fair. The reaction-type steam turbine was originated by Charles A. Parsons, and the first units were built in 1884 and 1885 at the shops of Messrs. Clark, Chapman, Parsons, and Company, Gates Head Works, England. Only two are known to exist today, the first ever made, which is at South Kensington Museum, London, and the one now at the World's Fair, which was the fifth to be built. It is the property of the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., having been presented to the company in 1912 by Mr. Parsons himself. The unit, shown in the accompanying illustration, operated at 18,000 rpm and was rated ten effective horsepower. It is a noncondensing steam turbine direct-coupled to a Parsons d-c dynamo. The unit is 12 inches wide, with an over-all length of 5 feet; the dynamo is 14½ inches wide.

public or confined to engineers was raised by Mr. Bell of the Muscle Shoals Section. The ensuing discussion seemed to indicate that the general practice is to invite anyone interested to the technical meetings, but that occasionally recreational or social meetings are held to which only members and their families are invited.

The meeting was adjourned at 1:50 p.m. so that the delegates could return to the second session of the annual conference of officers, delegates and members.

Executives to Serve ASA as Advisory Body

Thirteen prominent executives, representing manufacturing, finance, retailing, and education, will serve as an advisory committee for the American Standards Association, according to recent announcement. Reorganization of the advisory committee to its present form is indicative of the growing recognition of the importance of standardization as a managerial function. The ASA was organized in 1918 by five of the engineering societies, the AIEE having taken the first steps toward its formation. It was then called the American Engineering Standards Committee. Trade associations and the Federal Government were next brought into its work, and later the organization was given its present name and structure, with responsibility for policy centering in a board of directors of industrial executives. Its work has since been extended increasingly to problems which affect management and merchandising: safety, prevention of occupational diseases, traffic regulations, building codes, and, most recent, standards for consumer goods.

The committee, which brings major executives into the national standardization program as the final source of advice, has the following members:

Howard Coonley, chairman of board, Walworth Company, New York, N. Y., *chairman*; Ralph Budd, president, Chicago, Burlington and Quincy Railroad, Chicago, Ill.; F. L. Carlisle, chairman of board, Consolidated Edison Company of New York, N. Y.; Doctor Karl T. Compton (F'31) president, Massachusetts Institute of Technology, Cambridge, Mass.; Lammot du Pont, president, E. I. du Pont de Nemours and Company, Wilmington, Del.; Lincoln Filene, president, William Filene's Sons Company, Boston, Mass.; W. S. Gifford (A'16) president, American Telephone and Telegraph Company, New York, N. Y.; L. A. Lincoln, president, Metropolitan Life Insurance Company, New York, N. Y.; J. H. McGraw, Jr., president, McGraw-Hill Publishing Company, New York, N. Y.; A. W. Robertson (A'27) chairman of board, Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa., and New York, N. Y.; A. P. Sloan, Jr., chairman of board, General Motors Company, New York, N. Y.; E. R. Stettinius, chairman of board, United States Steel Corporation, New York, N. Y.; W. C. Teagle, chairman of board, Standard Oil Company of New Jersey, New York, N. Y.

Tentative Program for District Meeting at Scranton

For the AIEE Middle Eastern District meeting, to be held in Scranton, Pa., October 11–13, 1939, the tentative technical program consists of sessions on mining, rating of electrical machinery and apparatus, power transmission and distribution, meters, relays and protection, and electrical apparatus. In the session on rating of electrical machinery and apparatus, P. L. Alger, chairman of standards co-ordinating committee 4 will give a résumé of the work of the standards committee in revising AIEE Standard No. 1. Arrangements also are being made for a meeting of co-ordinating committee 4 to be held on Wednesday morning, October 12. In addition to the technical program there will be inspection trips, reception and entertainment, informal dinner-dance, and other social events and trips for women guests.

Members of the District meeting committee are: I. Melville Stein, H. A. Dambly, E. F. DeTurk, W. A. Furst, E. E. Kimberly, J. W. Mills, H. S. Phelps, J. E. Treweek E. F. Weaver.

AIEE Baltimore Section Becomes Maryland Section

Upon recommendation of the AIEE Sections committee, the board of directors at its meeting June 29, 1939, authorized a change of name of the Baltimore Section to the Maryland Section. No change in Section territory is involved. The Section includes Baltimore, Frederick, Carroll, Cecil, Harford, Howard, Anne Arundel, Kent, Queen Anne's Talbot, Caroline, Dorchester, and Wicomico counties in Maryland; Kent and Sussex counties in Delaware; and York, Lancaster, and Adam counties in Pennsylvania.

The Baltimore Section was organized December 16, 1904. The new officers of the Maryland Section for the term 1939–40 are: *chairman*, H. A. Frey (A'28) electrical engineer, Locke Insulator Corporation, Baltimore; secretary, G. R. Page (A'30) engineer, Point Breeze Works, Western Electric Company, Baltimore.

Great Lakes District Meeting and Branch Convention

Minneapolis will be host to a three-day meeting and Student Branch convention of the Great Lakes District, AIEE September 27–29, 1939. Hotel Nicollet will be meeting headquarters.

Tentative arrangements are being made for a program of five technical sessions, two student sessions, inspection trips, entertainment, and sports. The detailed program will be announced later.

The city of Minneapolis with its modern and convenient transportation facilities provides an ideal location for the meeting. Sight-seeing by visitors may include the flour mills located on the Mississippi River at St. Anthony Falls, the University of Minnesota, the Minneapolis Symphony Orchestra, the Minneapolis boulevard and park systems, historic Fort Snelling, the "Twin City" of St. Paul, Lake Minnetonka, Minnehaha Falls.

ACS Will Celebrate Goodyear Centenary. A special program in honor of the hundredth anniversary of Charles Goodyear's discovery of vulcanization of rubber will feature the 98th meeting of the American Chemical Society, to be held in Boston, Mass., September 11–15. Doctor Karl T. Compton (F'31) president of Massachusetts Institute of Technology, will be one of the speakers on the centenary program. A symposium on vulcanization will also be part of the technical program of the meeting, which will cover progress in all major spheres of chemical science.

Future Meetings of Other Societies

American Chemical Society. Fall meeting, September 10–15, Boston, Mass.

American Institute of Physics. Temperature symposium, November 2–4, New York, N. Y.

American Society of Civil Engineers. International fall meeting, September 4–9, New York, N. Y.

American Society of Mechanical Engineers. Fall meeting, September 4–8, New York, N. Y.

Joint meeting ASME Fuels Division, AIME Coal Division, October 5–7, Columbus, Ohio.

Association of Iron and Steel Engineers. Annual convention, September 26–29, Pittsburgh, Pa.

Conference on Electrical Insulation (National Research Council). November, Cambridge, Mass.

Electrochemical Society. Fall convention, September 11–13, New York, N. Y.

Illuminating Engineering Society. 33d annual convention, August 21–25, San Francisco, Calif.

Institute of Radio Engineers. 14th annual convention, September 20–23, New York, N. Y.

Fall meeting, November 13–15, Rochester, N. Y.

National Electrical Contractors Association. October 9–12, Philadelphia, Pa.

National Electrical Manufacturers Association. October 23–27, Chicago, Ill.

National Safety Council. October 16–20, Atlantic City, N. J.

Société Française des Électriciens. Television meeting, November, Paris, France.

Society of Automotive Engineers. National aircraft production meeting, October 5–7, Los Angeles, Calif.

Electrical Insulation Conference to Meet

The Conference on Electrical Insulation, sponsored by the division of engineering and industrial research of the National Research Council, will hold its next annual meeting early in November 1939 at Cambridge, Mass., Chairman J. B. Whitehead has announced. The exact dates will be announced later. Members of the Conference will be guests of Harvard University.

Members have been asked to furnish information about research now under way, upon which reports may be made in the technical program of the meeting. This may be research by members and their associates, or any other research or activity concerned with electrical insulation that may be of interest to the meeting. Both finished papers and informal progress reports will be included in the program.

Lightning Generator at New York Fair

Use of new materials and improved design, resulting in reduced size for increased capacity, gives additional interest to the modern 10,000,000-volt artificial-lightning generator being used in public demonstrations by the General Electric Company in Steinmetz Hall at the New York World's Fair. Two units of cylindrical capacitors, piled in six vertical stacks 34 feet high, occupy less than one-fourth the floor space required for the square metal containers used in former lightning generators, but have 40 per cent greater capacity. The stored energy of the new generator is 165,000 watt-seconds. It takes only 15 seconds for the voltage to reach full value

before discharging across a 30-foot gap, as compared with 150 seconds for the earlier unit. Looking up at one bank of capacitors, the accompanying illustration shows the Herkolite cylinders interposed between units for insulation. The insulators are painted black and all exposed metal parts are stainless steel. As the current is short circuited when all capacitors are fully charged, flashovers occur between small spheres projecting from rods in the center.

N. C. Club Celebrates Anniversary. The Engineers Club of Western North Carolina, organized May 16, 1938, reported on its first anniversary an increase from 43 to 70 members, successful professional and social activities, and a sound financial position. The club was established as a professional organization in which all branches of engineering are represented. C. E. Waddell (A'02, F'12) consulting engineer, Asheville, N. C., is a member of the board of directors.

Current Items From American Engineering Council

Changes in Patent System Before Congress

A series of bills proposing simplification and speeding up of the procedure by which patents are issued by the Patent Office have been introduced in Congress. These bills embody suggestions made by Commissioner of Patents Conway P. Coe in testimony before the Temporary National Economic Committee and are supported, in general, by the patent bar. Since very little opposition has been voiced, it is hoped to pass at least some of the bills before Congress adjourns.

The principal changes proposed are:

1. Reclassification of Patent Office records by a force of 25 additional examiners whose entire time shall be devoted to this task. Modernization of the classification system, now admittedly antiquated and confusing, is expected to expedite the examination of future patent applications and thus conserve the time of both examiner and applicant. (H.R.6721.)

2. Reduction in the time allowed for public use of an invention before applying for a patent from two years to one year. (H.R.6872.)

3. Simplification of the present interference practice, which decides which of two conflicting applications shall be granted, by referring the matter to a three-man board of interference examiners and issuing a patent immediately in consonance with their decision. Thereafter the losing party can, if he wishes, appeal the matter, but the present long delay in issuance whenever such appeal is taken is eliminated. (H.R.6873.)

4. Reduction of the time for paying the final patent fee from six to three months after notice that the application has been approved. The Commissioner is given discretion to extend this time an additional year if justification for the delay is demonstrated. (H.R.6874.)

5. Limitation of the time for copying claims into an application from prior patents to those

issued within one year, rather than two. (H.R.-6875.)

6. Reduction in the allowed time for responding to Patent Office communications from the present six months to not less than 30 days, at the discretion of the Commissioner. (H.R.6878.)

7. Termination of the life of a patent at 17 years after date of issue or 20 years after date of application, whichever is shorter. (S.2688.)

8. Setting up a single Court of Patent Appeals to which shall be referred all appeals from decisions of United States District Courts regarding patent cases. (S.2687.)

Bills noted in items 1 to 6, inclusive, were passed by the House on July 6; those in items 7 and 8 were approved by the Senate Patents Committee on July 6.

Utility Study Issued

A statistical study of the operations of 385 privately owned electric utility companies, comprising about nine-tenths of the industry, for the calendar year 1937 has been published in two volumes by the Federal Power Commission and is available at $2 per set.

Covering companies with annual revenues of $250,000 or more, the report reveals total electric revenues of $2,157,277,266 from the operation of total assets valued at $16,873,-384,102. Outstanding securities total $13,-378,579,835, of which bonds and other long-term obligations account for $6,850,194,447; preferred stocks $2,125,431,564; common stocks $4,306,363,835.

Residential customers during the year averaged 19,627,633 in number, and paid $645,748,799 for 14,821,890,000 kilowatt-hours of power, an average of 755 kilowatt-hours per year per customer at an average cost of 4.3 cents. Commercial and industrial sales accounted for 65,202,088,000 kilowatt-hours of consumption, $1,105,092,-543 of revenue, an average price of 1.7 cents.

The Commission is also preparing to publish a national electric rate book showing the residential, commercial, and industrial electric rates charged by all utility companies in the United States, whether privately or publicly owned. This material will be bound in a loose-leaf binder so that subsequent revisions can easily be substituted to keep the volume up to date. The price will be $15, including any supplements that may be issued up to December 31, 1939; subsequent supplements will cost $7.50 per year. Separate issues covering individual states will also be available at from $1 to $2 each, depending on size.

John Carmody Appointed Public Works Head

On July 1 general supervision of public works activities of the federal government was vested in John M. Carmody, engineer and former head of the Rural Electrification Administration, who was named by President Roosevelt Administrator of the Federal Works Administration, created under the terms of the Reorganization Act. The position carries a salary of $12,000, one of the highest outside the cabinet and the Supreme Court, and is expected to become one of the most important posts in the Federal establishment.

An avowed liberal, Mr. Carmody left a position as labor relations executive with the Davis Coal and Coke Company to become editor of *Coal Age* and also *Factory and Industrial Management*. In 1933 he was appointed chairman of the Bituminous Coal Labor Board, and later became chief engineer for the Civil Works Administration and its successor, the Federal Emergency Relief Administration. He subsequently served as a member of the National Mediation Board and the National Labor Relations Board, resigning to head the Rural Electrification Administration in 1936. He is a past president of the Society of Industrial Engineers and a member of the Taylor Society and the American Association for Labor Legislation.

Appointed to head the second new agency under the Reorganization Act, the Federal Loan Agency, was Chairman Jesse Jones of the Reconstruction Finance Corporation.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and the other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

A D-C Application of Hyperbolic Functions

To the Editor:

Three problems in two-wire d-c distribution have always interested the writer. The solution in every case consists in obtaining the voltages and currents everywhere along the line.

Problem 1: Two or more loads kw_1 and kw_2 are distant l_1 and l_2 from a generator at voltage E_G. The student meets this problem for the first time in his elementary course in direct currents. It can be solved by a fourth-degree equation in E_1 or E_2, also by a fourth-degree equation in I_1 or I_2. If there are three loads, the solution involves a sixth-degree equation, and so on. These equations can be solved most quickly by the cut-and-try method.

Problem 2: A line has a constant resistance per foot of r ohms; it has a uniformly distributed load per foot of i amperes. This line has a uniformly increasing current toward the generator, also a cumulatively increasing voltage toward the generator. By using a small differential strip dx and integrating throughout the length of the line L, a solution is easily obtained; viz., voltage drop on line is equal to $\frac{1}{2}RI$, where $R = 2Lr$ is the resistance of the line, and $I = iL$ is the current at the generator. In this particular case the line is open at the load.

Problem 3: A line has a uniform resistance and a uniformly distributed load of constant conductance (or resistance). In this case the current increase from load toward generating station is a graph of hyperbolic sines (not uniform as in the second case) while the voltage increase from load toward generating station is a graph

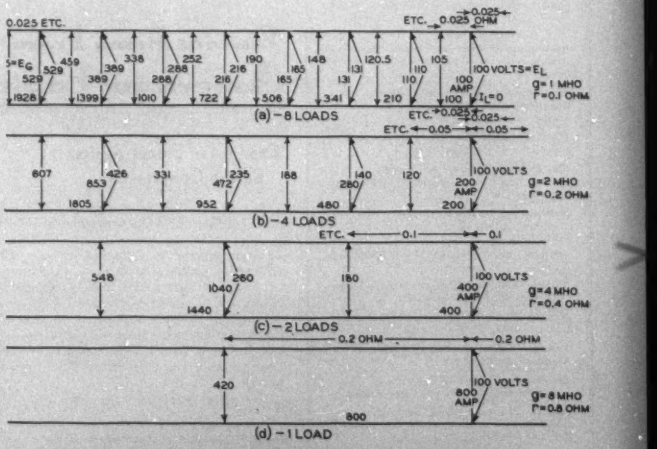


Figure 1. The true voltage and current distribution along the line

of hyperbolic cosines (not cumulatively increasing as in the second case). This is the very practical case of the d-c or a-c network; also, to a lesser degree, the residential lighting circuit.

The purpose of this discussion is to solve problem 3 by using the hyperbolic functions; also to show how accurate they become when there are eight loads, four loads, two loads, and one load.

The theory needed is as follows:

$$E_G = E_L \cosh \theta + I_L Z_0 \sinh \theta \text{ vector volts}^1 \quad (1)$$

$$I_G = I_L \cosh \theta + E_L/Z_0 \sinh \theta \text{ vector amperes} \quad (2)$$

where E_G and I_G equal voltage and current respectively at generator end of line, and E_L and I_L equal voltage and current respectively at load end of line. The line is considered to be open at the load (see figure 1), in which case $I_L = 0$ and hence equation 1 becomes

$$E_G = E_L \cosh \theta \quad (1a)$$

and equation 2 becomes

$$I_G = E_L/Z_0 \sinh \theta \quad (2a)$$

Let

g = conductance of each load in mhos *per load* (corresponds to leakage conductance in transmission);

and

r = resistance of line in ohms *per load*.

Now

$\alpha = \sqrt{gr}$, vector numeric, expressed in real hyperbolic radians *per load*.

And

$\theta = al$, vector numeric, where l is the number of loads (length of line in transmission).

$Z_0 = \sqrt{r/g}$, vector ohms.

α is called the attenuation constant of line *and load* (line in transmission).

Z_0 is called the characteristic *resistance* of the line (characteristic impedance in transmission).

The true data as calculated for a specific problem is given: for an eight-load case in figure 1*a*; for a four-load case in figure 1*b*; for a two-load case in figure 1*c*; and for a one-load case in figure 1*d*.

The use of equations 1*a* and 2*a* will give an accurate result for an infinite number of loads only.

In table I, *a*, column 7, E_G is given, figure 1 (i.e., 625 for the eight-load case) and E_L is calculated ($I_L = 0$), column 8.

In column 9, E_L is given, figure 1 (i.e., 100 for each case) and E_G and I_G are calculated at each load, columns 10 and 12.

Comments on Table and Figures

Column 2, $\alpha = \sqrt{gr} = \sqrt{1 \times 0.1} = 0.316$ for part 1*a*, table I; $\alpha = \sqrt{2 \times 0.2} = 0.632$ for part 1*b*; etc., see figure 1.

Column 3, $\theta = al = 8 \times 0.316 = 2.53$.

Column 4, $Z_0 = \sqrt{r/g} = \sqrt{0.1/1} = 0.316$ for part 1*a*; $Z_0 = \sqrt{0.2/2} = 0.316$ for part 1*b*; etc.

Columns 8 and 9 show how the hyperbolic solution, $E_L = 99+$, compares with the true solution, $E_L = 100$. Per cent error = 1−.

Columns 10 and 11 show how the hyperbolic solution, $E_G = 632$, compares with the true solution, $E_G = 625$. Per cent error = 1−.

Columns 12 and 13 show how the hyperbolic solution, $I_G = 1{,}970$, compares with the true solution, $I_G = 1{,}928$. Per cent error = 2+.

Broken curve 1, figure 2, is E_G true, obtained from figure 1*a* at each load for the eight-loads case, column 11.

Smooth curve 2, figure 2, is E_G calculated, by the hyperbolic solution at each load, column 10.

Broken curve 3, figure 2 is I_G, true, obtained from figure 1*a* at each load for the eight-loads case, column 13.

Smooth curve 4, figure 2, is I_G calculated, by the hyperbolic solution at each load, column 12.

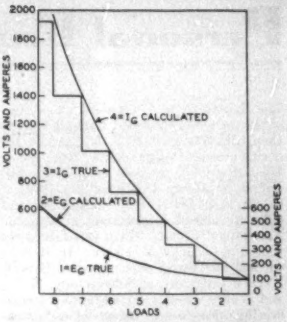


Figure 2. Voltage and current distribution along the line, both true and calculated by the hyperbolic method

Curves 1 and 2 practically coincide; curves 3 and 4 practically coincide at each load. All calculations were made with slide rule; no interpolation was used in getting $\cosh \theta$ and $\sinh \theta$.

Conclusions

1. The hyperbolic solution may be used for eight loads or more than eight with very little error in E_L, when E_G is known; table I, part 1*a*, column 8.

2. The hyperbolic solution may be used for voltage and current distribution along the line for eight loads or more than eight with very little error in E_G and I_G, when E_L is known; curves 1, 2, 3, 4, figure 2.

3. When loads greater than eight in number are to be dealt with, this method, using hyperbolic functions, saves much time over a longhand method, figure 1, and gives sufficiently accurate results; this is especially true when practical values of g and r are used. The values $g = 1$ mho, $r = 0.1$ ohm, were chosen to simplify calculations. Practical values of g and r for the eight or more load case would make the hyperbolic method almost imperative.

4. The hyperbolic solution can be applied to the calculation of currents in a network, voltages along the network, lowest voltage in a network, voltage regulation, and so on.

5. It can be used just as readily on an Edison three-wire system as on a two-wire system.

6. It can be used for a-c circuits in low-voltage distribution; the charging current in this case is negligible and the actual load currents replace the leakage current.

Table I

	Part I. Given E_G, to calculate E_L (I_L = 0)								Part II. Given E_L (I_L = 0), to calculate E_G, I_G				
1	2	3	4	5	6	7	8		9	10	11	12	13
Loads	α	$\theta(=al)$	Z_0	$\cosh\theta$	$\sinh\theta$	True E_G (Fig. 1)	Calculated E_L ($= E_G/\cosh\theta$)		True E_L (Fig. 1)	Calculated E_G ($= E_L \cosh\theta$)	True E_G (Fig. 1)	Calculated I_G ($= E_L/Z_0 \sinh\theta$)	True I_G (Fig. 1)
(*a*) Eight loads on line													
at 8th	0.316	2.53	0.316	6.32	6.24	625	99+		100	632	625	1,970	1,928
at 7th	0.316	2.21	0.316	4.61	4.50	459	99+		100	461	459	1,420	1,399
at 6th	0.316	1.90	0.316	3.42	3.27	338	99+		100	342	338	1,034	1,010
at 5th	0.316	1.58	0.316	2.53	2.32	252	99+		100	253	252	733	722
at 4th	0.316	1.26	0.316	1.91	1.62	190	99+		100	191	190	512	500
at 3d	0.316	0.95	0.316	1.49	1.10	148	100−		100	149	148	347	341
at 2d	0.316	0.63	0.316	1.21	0.676	120.5	100−		100	121	120.5	214	210
at 1st	0.316	0.316	0.316	1.05+	0.321	105	100−		100	105	105	102	100
(*b*) Four loads on line													
at 4th	0.632	2.53	0.316	6.32	6.24	607	96		100	632	607	1,970	1,805
at 3d	0.632	1.90	0.316	3.42	3.27	331	97		100	342	331	1,034	952
at 2d	0.632	1.26	0.316	1.91	1.62	188	99		100	191	188	512	480
at 1st	0.632	0.63	0.316	1.21	0.676	120	100−		100	121	120	214	200
(*c*) Two loads on line													
at 2d	1.265	2.53	0.316	6.32	3.24	548	87		100	632	548	1,970	1,440
at 1st	1.265	1.26	0.316	1.91	1.62	180	95		100	191	180	512	400
(*d*) One load on line													
at 1st	2.53	2.53	0.316	6.32	6.24	420	66		100	632	420	1,970	800

References

1. Application of Hyperbolic Functions to Electrical Engineering, A. E. Kennelly. McGraw-Hill Book Company, New York, 1925. Third edition, page 12.

2. Principles of Electric Power Transmission and Distribution, L. F. Woodruff. John Wiley and Sons, Inc., New York, 1925. First edition, page 132.

Very truly yours,

J. L. Beaver (A'14, F'26)

(Professor of electrical engineering, Lehigh University, Bethlehem, Pa.)

Personal Items

T. F. Barton (A'12, F'30) assistant manager of the New York district, General Electric Company, New York, N. Y., has been elected a vice-president of the AIEE, representing District number 3, New York City. Mr. Barton was born December 25, 1885, at Orangeburg, S. C., and studied electrical and mechanical engineering at Clemson Agricultural College, where he received the degree of bachelor of science. In 1906 he entered the testing department of General Electric Company, at Schenectady, N. Y., and in 1909 was transferred to the d-c engineering department. He served in the engineering department of the company's New York office from 1911 to 1917, when he returned to Schenectady as a section head in the central-station-engineering department. He became district engineer of the New York district in 1927, and in 1939 was appointed to his present position. Mr. Barton has twice won Charles A. Coffin Foundation awards for contributions to the electrical industry. He was chairman of the AIEE New York Section in 1932–33, chairman of the 1939 winter convention committee, and is a member of the committees on economic status of the engineer and on legislation affecting the engineering profession.

M. E. Leeds (A'01, F'26) founder and president of the Leeds and Northrup Company, Philadelphia, Pa., has become chairman of the board of directors in an expansion of the company's executive organization. Born in Philadelphia March 6, 1869, Doctor Leeds received the degree of bachelor of science from Haverford College in 1888, studied at the University of Berlin in 1892–93, and received the honorary degree of doctor of engineering from Brooklyn Polytechnic Institute in 1936. After two years of teaching, Doctor Leeds entered the scientific-instrument business in 1890 with Queen and Company, Philadelphia, remaining with the company until 1899. In that year he organized and became managing partner of Morris E. Leeds and Company, which in 1903 became the Leeds and Northrup Company, with Mr. Leeds as president. He holds numerous patents on electrical measuring instruments and associated equipment and in 1920 was awarded the Edward Longstreth medal of the Franklin Institute, Philadelphia, of which he is a member. He received the Gant Medal of the Institute of Management in 1936. He is also a member of the American Association for the Advancement of Science, the American Physical Society, American Society for Steel Testing, American Society for Testing Materials, academy of Natural Sciences, and Phi Beta Kappa.

R. P. Brown (A'10, M'13) has been appointed the first secretary of the new Department of Commerce of the Commonwealth of Pennsylvania. He is chairman of the board of the Brown Instrument Company, Philadelphia, Pa. Born in Philadelphia September 26, 1884, he studied at Drexel Institute, and in 1904 was employed by Edward Brown, manufacturer of thermoelectric pyrometers. In 1906 he became a member of the firm of Edward Brown and Son. The firm became the Brown Instrument Company in 1910 with Mr. Brown as its president, a position he held until recently. He is also vice-president and director of the Minneapolis-Honeywell Regulator Company, an associated firm. He holds the patents for various electrical instruments, and is a member of The American Society of Mechanical Engineers, American Society for Testing Materials, and the Franklin Institute, Philadelphia.

A. M. Dudley (A'08, F'13) engineering representative in the patent department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been awarded the honorary degree of doctor of engineering by the University of Michigan. Doctor Dudley has received the degrees of bachelor of science in engineering (1902) and electrical engineer (1931) from the University of Michigan, and master of science (1933) from the University of Pittsburgh. He has been with the Westinghouse company since 1904, in various engineering positions. He has taught in the Westinghouse design and engineering schools and is a Westinghouse lecturer in electrical engineering at the University of Pittsburgh, Pittsburgh, Pa. He assisted with the accrediting program of the Engineers Council for Professional Development, and was for three years a member of the national council of the Society for the Promotion of Engineering Education.

H. L. Andrews (A'16, M'26) vice-president of General Electric Company, has been placed in charge of the company's appliance and merchandise department, with headquarters in Bridgeport, Conn. A native (1889) of Boonville, Mo., he received the degree of bachelor of science in electrical engineering from the University of Missouri in 1910, and entered the testing department of General Electric at Schenectady, N. Y. He has been with the company continuously, becoming assistant engineer in 1925, chief engineer, transportation engineering department, 1929, and from 1934 until his present appointment was vice-president in charge of transportation activities. He has been vice-chairman of the company's sales committee for three years.

C. S. Redding (A'12) has been made president of Leeds and Northrup Company, Philadelphia, Pa. Born in Philadelphia in 1883, Mr. Redding received the degree of bachelor of science in electrical engineering from the University of Pennsylvania in 1906. Before entering college he spent a year in the laboratory of Morris E. Leeds and Company, Philadelphia, predecessor of Leeds and Northrup, and in 1909, after two years as an instructor in mechanical engineering at the University of Pennsylvania, Philadelphia, he returned to Leeds and Northrup. He has since held executive positions in every division of the company's activities, as sales manager, factory manager, second vice-president (1918) treasurer (1922–24), and vice-president in charge of research and engineering from 1928 to the present. He is a member of the American Physical Society, American Association for the Advancement of Science, and the Franklin Institute.

D. W. McLenegan (A'24, M'31) has been made manager of engineering sales in the air-conditioning department of the General Electric Company, in the new divisional organization set up after the consolidation of the company's air-conditioning and commercial-refrigeration activities at Bloomfield, N. J. Mr. McLenegan received the degree of bachelor of science in mechanical engineering from the University of Wisconsin, Madison, and after two years spent teaching engineering mathematics at that institution he entered the research laboratories of General Electric at Schenectady, N. Y., in 1922. He was transferred to the industrial-engineering department the following year, and in 1938 was made manager of the company's air-conditioning institute at Bloomfield, N. J.

H. B. Gear (A'01, F'20), vice-president in charge of operating and engineering, Commonwealth Edison Company, Chicago, Ill., has been awarded the honorary degree of doctor of laws by Marietta College. Doctor Gear received the degree of bachelor of arts from Marietta College in 1892 and the degree of mechanical engineer from Cornell University in 1895. He entered the service of the Chicago Edison Company, predecessor of Commonwealth Edison, in 1895 as electrical inspector, becoming chief inspector, engineer of distribution for Commonwealth Edison, and in 1935 vice-president. He was a director of the AIEE, 1934–38, and is a member of the Edison Medal committee and the commission on the Washington Award.

J. E. Lawson (A'22) vice-president and general manager of the Canadian Niagara Power Company, Ltd., Niagara Falls, Ont. Can., has been elected president of the Canadian Electrical Association. Mr. Lawson was born in Clinton, N. Y., in 1881, and began his association with the electrical industry as a helper with General Electric Company in 1903. During the next four years he was with the Canadian Niagara Power Company and Canadian General Electric Company, as well as General Electric. In 1907 he became an electrical fitter for Canadian Niagara Power Company and has remained with the company ever since, as foreman, chief operator, superintendent, and vice-president.

D. M. Simmons (A'22, F'28) chief engineer, General Cable Corporation, New York, N. Y., has been awarded the honorary degree of doctor of engineering by Princeton University. Doctor Simmons received the degrees of bachelor of arts (1911) and electrical engineer (1913) from Princeton. He was with the Standard Underground Cable

M. E. LEEDS

H. L. ANDREWS

C. S. REDDING

T. F. BARTON

R. P. BROWN

Company from 1913 to 1927, when it joined with other companies to form the General Cable Company. In 1928 he was made director of high-voltage engineering in the latter company and in 1930 chief consulting engineer. He is a member of the AIEE committee on power transmission and distribution and of the publication committee.

E. C. Goodale (A'27) has been awarded AIEE District number 9 prize for best paper, for the paper "A Graphical Method of Multiplying and Dividing Complex Quantities, and Its Use in the Solution of Impedance Networks," presented at a meeting of the Seattle (Wash.) Section, March 22, 1938. Mr. Goodale, who is an inspector for the Puget Sound Power and Light Company, Olympia, Wash., studied engineering at Cornell University and has been employed in various engineering capacities by the Syracuse (N. Y.) Lighting Company, Southern California Edison Company, and others, before going with the Puget Sound company in 1926.

W. H. Harrison (A'20, F'31) recently received the honorary degree of doctor of laws from Notre Dame University. Doctor Harrison, who is vice-president and chief engineer of the American Telephone and Telegraph Company, has been with various companies of the Bell System since 1909. He was graduated from Pratt Institute in 1915 in industrial electrical engineering. AIEE past-president (1937–38), he has a long record of active service in the Institute, and is at present a director, Institute representative on the American Engineering Council, and member of several committees.

C. W. LaPierre (A'28) was awarded AIEE District number 1 prize for best paper, jointly with co-author A. P. Mansfield, for the paper "Photoelectric Weft-Straightener Control" presented at the North Eastern District meeting, Lenox, Mass., May 18, 1938. Mr. LaPierre, who studied engineering at the University of Missouri, has been with General Electric Company, in Schenectady, N. Y., and Philadelphia, Pa., since 1923. He is at present an electrical engineer at the company's Schenectady plant.

E. W. Seeger (A'16, F'36) has been appointed manager of the development department, Cutler-Hammer, Inc., Milwaukee, Wis. Mr. Seeger has been with the company continuously since his graduation from Ohio State University in 1913, and prior to this appointment was in charge of the production engineering department. A biographical sketch of him appeared in the February issue, page 91.

C. P. Cooper (A'08, M'21) vice-president, American Telephone and Telegraph Company, New York, N. Y., has been awarded the honorary degree of doctor of science by Ohio State University. Doctor Cooper was graduated from that institution in 1907 with the degree of mechanical engineer in electrical engineering, and was an instructor for a year at New Hampshire State College, Durham, before becoming a plant engineer for the New York Telephone Company. He has been associated with the Bell System ever since, assuming his present position in 1926.

P. P. Koliss (Enrolled Student), with co-author Joseph Ezen, shared in AIEE District number 1 prize for Branch paper, for the paper "Analysis of an Electron-Tube-Controlled Induction Motor," presented at the North Eastern District meeting, Lenox, Mass., May 20, 1938. Mr. Koliss, who received the degree of bachelor of science at Worcester Polytechnic Institute in 1939, is doing graduate study leading to the degree of master of science at that institution.

W. S. Gifford (A'16), president of the American Telephone and Telegraph Company, New York, N. Y., has been appointed a member of the American Standards Association's newly organized advisory committee of executives. Doctor Gifford was also recently made honorary chancellor of Union College for 1939–40, and awarded the honorary degree of doctor of civil law by that institution.

P. B. Harwood (M'36) has been appointed manager of the engineering department, Cutler-Hammer, Inc., Milwaukee, Wis. Mr. Harwood has been with the Cutler-Hammer company since 1917 and prior to his present appointment was assistant in charge of the production engineering department. A biographical sketch of him appeared in the February issue, page 92.

G. T. Shoemaker (M'20), president, the United Light and Power Service Company, Chicago, Ill., has been nominated a manager of The American Society of Mechanical Engineers for 1940. Mr. Shoemaker is also vice-president and general manager of the United Light and Power Company and of several of its subsidiaries. A biographical sketch of him appeared in the October 1938 issue, page 435.

Francis Hodgkinson (A'02) has been nominated a vice-president of The American Society of Mechanical Engineers for the 1940 term. Mr. Hodgkinson, who is a consulting mechanical engineer in New York, N. Y., was awarded the Holley Medal of the ASME in 1938. A biographical sketch of him appeared in the December 1938 issue, page 522.

J. D. Mortimer (A'00) has been elected a director of Associated Gas and Electric Company, New York, N. Y. Mr. Mortimer, formerly president and later director of the North American Company, New York, has had a long career in the public utility industry. A biographical sketch of him appeared in the January issue, page 52.

David Sarnoff (M'23) has been awarded the honorary degree of doctor of science by Suffolk University. Doctor Sarnoff, president of the Radio Corporation of America, has been connected with radio in various capacities since 1906. He studied engineering at Pratt Institute. He is a member of the Institute of Radio Engineers.

R. J. Greer (A'36) has been employed as a junior hydraulic engineer by the Water Resources Branch of the United States Geological Survey, Boston, Mass. He was formerly an inspector on water construction at the Cape Cod Canal, Buzzards Bay, Mass., for the United States Engineering Department.

A. W. Robertson (A'27) chairman of the board, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed a member of the advisory committee of executives, recently organized by the American Standards Association.

F. T. McNamara (A'39), assistant professor of electrical engineering, Yale University, New Haven, Conn., has been appointed AIEE representative on the sectional committee on radio-electrical co-ordination—C65, operating under American Standards Association procedure.

K. T. Compton (F'31), president, Massachusetts Institute of Technology, Cambridge, Mass., has been appointed a member of the newly organized advisory committee of the American Standards Association.

W. E. Keith (A'25) has been appointed assistant to the vice-president, personnel department, New England Telephone and Telegraph Company, Boston, Mass. He has been with the company since 1923, and prior to this appointment was unit manager in Boston.

W. H. Sammis (A'20, M'38) has been elected chairman of the Modern Kitchen Bureau of the Edison Electric Institute for 1940. He is vice-president of the Commonwealth and Southern Corporation, New York, N. Y.

H. C. Hamilton (A'23, M'26) has been elected treasurer of the Engineering Societies of New England, Inc., for the year beginning June 1, 1939. Mr. Hamilton is head of the laboratory, Boston Edison Company, Boston, Mass.

Frank Walsh (A'26, M'30) has been elected Washington State vice-president of the Northwest Electric Light and Power Association. Mr. Walsh is division manager, Puget Sound Light and Power Company, Bellingham, Wash.

F. S. Himebrook (A'32) formerly electrical engineer with the General Industries Company, Elyria, Ohio, is now electrical engineer with the Master Electric Company, Dayton, Ohio,with which he has previously been associated.

G. R. Canning (A'32) has been elected president of the Cleveland (Ohio) Engineering Society for the coming year. He is transmission engineer, Ohio Bell Telephone Company, Cleveland.

H. L. Wilcox (M'37) has been elected treasurer of the Cleveland (Ohio) Engineering Society for 1939–40. He is assistant chief engineer, Electric Controller and Manufacturing Company, Cleveland, Ohio.

O. B. Coldwell (A'03, F'12) has been elected Oregon State vice-president of the Northwest Electric Light and Power Association. He is vice-president of the Portland (Ore.) Electric Power Company.

Obituary

Arthur Edwin Kennelly (A'88, M'99, F'13, HM'33) professor emeritus of electrical engineering at Harvard University and Massachusetts Institute of Technology, died in Boston, Mass., June 18, 1939, after a long illness. (The notice which appeared in the July issue incorrectly stated the date of Doctor Kennelly's death as April 18, 1939.) He was born near Bombay, India, December 17, 1861, and received his early education in schools in England, Scotland, France, and Belgium. He was awarded the honorary degree of doctor of science by the University of Pittsburgh in 1895, and by the University of Toulouse, France, in 1922, and received the honorary degree of master of arts from Harvard University in 1906. In 1875 he became assistant secretary of what is now The Institution of Electrical Engineers of Great Britain, and during the next twelve years was an operator for the Eastern Telegraph Company, assistant electrician in Malta, chief electrician of a cable-repairing steamer, and senior ship electrician on submarine cables. He came to the United States in 1887 and was engaged by Thomas A. Edison as principal electrical assistant. He was also consulting electrician for the General Electric Company. In 1894 he became associated with Edwin J. Houston in the firm of Houston and Kennelly. He was appointed professor of electrical engineering at Harvard University in 1902 and continued in that position until 1930. From 1913 to 1924 he was also professor of electrical engineering at Massachusetts Institute of Technology and was for some years director of electrical-engineering research and chairman of the faculty. During 1921–22 he represented seven co-operating American universities as first exchange professor in engineering and applied science at several French universities. Author and co-author of more than a score of books and over 300 technical papers, among his best-known contributions are the first application of complex numbers to Ohm's law in a-c engineering, in a paper presented before the AIEE in 1893, and the theory of the influence of solar ionization in the atmosphere on long-distance radio transmission, presented in 1902, which caused the so-called ionized layer, since verified experimentally, to be named the Kennelly-Heaviside layer. Active in AIEE affairs for 50 years, he had been a vice-president, a manager, president from 1898 to 1900, member of many committees, and AIEE representative on many organizations. He was the first chairman of the Institute's first standardization committee, and continued to be actively engaged both in the work of the AIEE for standardization and in international standardization of electrical units, representing the AIEE at many international conferences in the United States and other countries. He was also past-president of the Illuminating Engineering Society, Institute of Radio Engineers, American Metric Society; member of the American Association for the Advancement of Science, American Academy of Arts and Sciences, American Mathematical Society, and many others; and honorary member of the electrical-engineering societies of Great Britain, France, Germany, and Japan. In 1938 he was made honorary president of the International Electrotechnical Commission. His awards included the Institution Premium and Fahie Premium of The Institution of Electrical Engineers, Great Britain; Longstreth and Howard Potts medals, Franklin Institute; the cross of a Chevalier of the French Legion of Honor; the Mascart Medal of the Société Française des Électriciens, and the Edison Medal of the AIEE.

Julian Cleveland Smith (A'03, M'08, F'12) president, Shawinigan Water and Power Company, Montreal, Que., Can., died June 24, 1939. Born October 7, 1878, at Elmira, N. Y., he received the degree of mechanical engineer in electrical engineering from Cornell University in 1900. He was later awarded the honorary degree of doctor of laws by Queen's University, and by McGill University. After working as a draftsman for the West Manufacturing Company, Buffalo, N. Y., and in the electrial department of the Pan-American Exposition at Buffalo, he became in 1901 assistant to Wallace C. Johnson, consulting engineer, Niagara Falls, N. Y., and in 1902 went to Shawinigan Falls, Que., in charge of installation of high-voltage apparatus. He was made superintendent of the Shawinigan Water and Power Company in charge of the Shawinigan Falls power station in 1903, and four years later became general superintendent of that company and the allied companies of the system. He was subsequently chief engineer, vice-president, and general manager, and since 1933 had been president of the company. He was also president of Quebec Power Company, and vice-president of the Dominion Engineering Works, Ltd., and Dominion Bridge Company. He was a member of The Institution of Electrical Engineers of Great Britain, the American Society of Civil Engineers, and past-president of the Engineering Institute of Canada.

George Frederick Steele (A'10, M'27) died in Boston, Mass., June 25, 1939. A pioneer in the electrical industry, Mr. Steele was associated with the General Electric Company and its predecessors from 1885 until his retirement in 1931. Born in Derry, N. H., October 12, 1863, he was graduated in electrical engineering from Massachusetts Institute of Technology in 1885. He then entered the post-graduate course at the Thomson-Houston Company, Lynn, Mass., and the following year became superintendent of the New England Electric Company, agents of the Sprague Electric Railway and Motor Company. He continued with the New England Electric Company, becoming treasurer and then president, until 1890, when the parent company and the Edison Company consolidated to form the Edison General Electric Company. He was in charge of power work, railway, and lighting, in the Boston office of that organization until it consolidated with the Thomson-Houston company in 1892 to form the present General Electric Company. From 1892 to 1909 he was sales engineer in the Boston office of General Electric, and from 1909 to 1926 district manager of the power and mining department which became the industrial department. He retired from active work in 1926 but continued as a consulting engineer on special sales problems until 1931.

William Orlando Jacobi (A'10, M'30), electrical engineer, Omaha and Council Bluffs Street Railway Company, Omaha, Nebr., died April 10, 1939. He was born June 23, 1886, at Ludington, Mich., and graduated from Lewis Institute in 1909 with the degree of mechanical engineer. During the next two years he was engaged in electrical design and construction for the Pullman Company, Pullman, Ill., and as a draftsman for Stone and Webster in Minneapolis, Minn. In 1911 he was employed by the Omaha and Council Bluffs Street Railway Company on design and construction of power house and substations, later engaging in electrolysis test work. He became superintendent of electric lines and electrical engineer for the company in 1919, and was made secretary of the Omaha and Council Bluffs electrolysis committee in charge of testing.

Grove Cleland Carnahan (A'20), engineer and chief electrician, Illinois Publishing and Printing Company, Chicago, Ill., died April 15, 1939. Born in Apollo, Pa., October 18, 1884, and educated there, Mr. Carnahan began his connection with the electrical industry on construction work for the General Electric Company. After two years as construction foreman for C. G. Rush and Company, Chicago, Ill., he was employed in 1910 by the W. A. Jackson Company, Chicago, and three years later was made constructing foreman on central- and substation work, having charge of various projects in Illinois and Pennsylvania. He later became general foreman of construction for the company. In recent years he had been chief electrician for the Chicago Evening American, and The Chicago Herald and Examiner, before becoming engineer and chief electrician for the Illinois Publishing and Printing Company.

Roy Blake Bryant (A'09), proprietor, Bryant Light and Power Company, Dallas, Tex., died May 21, 1939. He was born in Nashville, Ark., February 14, 1887, and studied electrical engineering at the University of Arkansas. He was then employed as switchboard man by the Little Rock (Ark.) Railway and Electric Company, and later devoted some time to invention of street railway appliances. He was superintendent of the Eldorado Light and Power Company, manager of the Ashdown Light and Power Company, both in Arkansas, and with the DeKalb, Tex., Light and Power Company, of which he became proprietor after the World War. During the War he served in the United States Army, attaining the rank of captain. He subsequently became owner and manager of the Bryant Light and Power Company, Crandall, Tex., and later carried on that business in Dallas.

Spottswood Carmichael Foster (A'11), chief engineer, Bedford Pulp and Paper Company, Big Island, Va., died April 22, 1939. He was born April 23, 1886, in Fredericksburg, Va., and educated there, studying electrical engineering by correspondence. He was employed by the Rappahannock Electric Light and Power Company, Fredericksburg, in 1904 and later became superintendent. After the World War he was for a time a consulting engineer in Fredericksburg, and then became mechanical and electrical engineer for the Bedford Pulp and Paper Company, Colemans Falls, Va. He had been chief engineer for about three years.

J. N. Bourath (A'21), electrical engineer, Electro Dynamic Works of the Electric Boat Company, Bayonne, N. J., died May 13, 1939. Born in Belgium in May 1882, he graduated as an electrical engineer from the Electrotechnical Institute of the University of Liége. He was employed for a short time as draftsman by the Bell Telephone Company in Antwerp, Belgium. In 1911 he became associated with the Electro Dynamic Company, Bayonne, N. J., testing and inspecting electrical machinery, and later designed d-c motors and generators. He continued with the company and its successor until his death, at which time he was in charge of d-c engineering.

Giacomo Merizzi (A'12), director, Tecnomasio Italiano Brown Boveri, Milan, Italy, died recently, according to information received at Institute headquarters. He was born in Italy, January 6, 1866, and studied at the University and Polytechnical School of Turin. From 1898 to 1904 he was electrical engineer with Brown Boveri and Company. He became manager of Tecnomasio Italiano Brown Boveri in 1904, and had been director for more than ten years.

Toda Komaru (A'20), electrical designing engineer, Mitsubishi Electric Manufacturing Company, Ltd., Kobe, Japan, died March 14, 1939, according to information recently received. He was born May 1, 1893, in Kanazawa, Japan, and in 1917 was graduated in electrical engineering from the technical college of Tokyo Imperial University. Following graduation he entered the testing department of the Mitsubishi company as assistant electrical engineer, and the following year was transferred to the design office.

Frederick Milton Servos (A'19, M'27) chief electrical engineer, Rio de Janeiro Tramway, Light, and Power Company, Ltd., Rio de Janeiro, Brazil, died July 8, 1939, in St. Mary's Hospital, Brooklyn, N. Y. Mr. Servos was AIEE local honorary secretary for Brazil. A complete obituary notice will appear in the September issue.

Membership

Recommended For Transfer

The board of examiners, at its meeting on July 20, 1939, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Leonard T. Blaisdell, commercial vice-president, General Electric Company, Dallas, Tex.
Charles D. Brown, electrical engineer, Wisconsin Electric Company, Milwaukee.
Robert E. Doherty, president, Carnegie Institute of Technology, Pittsburgh, Pa.
Harry R. Fritz, general plant extension engineer, Southwestern Bell Telephone Company, St. Louis, Mo.
Earle S. Henningsen, engineer, General Electric Company, Schenectady, N. Y.
Terrence O. Kennedy, vice-president and general manager, Ohio Public Service Company, Cleveland, Ohio.
Clarence W. Kuhn, supervising engineer, Cutler-Hammer, Inc., Milwaukee, Wis.
Alexander C. Lanier, professor of electrical engineering, University of Missouri, Columbia.
James F. Lincoln, president, The Lincoln Electric Company, Cleveland, Ohio.
Humphreys Milliken, chief engineer and general superintendent, Montreal Light, Heat and Power Cons., Montreal, Canada.
Chester W. Rice, consulting engineer, General Electric Company, Schenectady, N. Y.
Martin Schiff, chief engineer, Century Electric Company, St. Louis, Mo.
Warner M. Skiff, retired, Palo Alto, Calif.
George E. Snider, electrical engineer, Ohio Public Service Company, Cleveland, Ohio.
H. R. Summerhayes, manager engineering division, central station department, General Electric Company, Schenectady, N. Y.
Robert Treat, engineer, General Electric Company, Schenectady, N. Y.
Herman L. VanValkenburg, vice-president and chief engineer, Square D Company, Milwaukee, Wis.
Wm. E. Wickenden, president, Case School of Applied Science, Cleveland, Ohio.

18 to Grade of Fellow

To Grade of Member

E. W. Allen, plant extension engineer, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Carl E. Arvidson, engineer, Commonwealth and Southern Corporation, Jackson, Mich.
David K. Blake, electrical engineer, General Electric Company, Schenectady, N. Y.
Karl A. Blind, electrical engineer, Harnischfeger Corporation, Miwaukee, Wis.
Fay B. Bramhall, engineer in charge of transmission laboratory, Western Union Telegraph Company, New York, N. Y.
Ralph L. Chantrill, engineer, Associated Electrical Industries (India) Ltd., Calcutta, India.
John Brown Cook, executive vice-president, Reliable Electric Company, Chicago, Ill.
John D. Harnden, assistant to manager, General Electric Company, Schenectady, N. Y.
Obed C. Haycock, assistant professor of electrical engineering, University of Utah, Salt Lake City.
Henry F. Herbig, research engineer, The North Electric Manufacturing Company, Galion, Ohio.
Luke F. Kennedy, relay application engineer, General Electric Company, Schenectady, N. Y.
Walter A. Kilbury, system operator, Cleveland Electric Illuminating Company, Ashtabula, Ohio.
Hector John MacLeod, head, department of electrical and mechanical engineering, The University of British Columbia, Vancouver, B. C., Canada.
Donald E. Moat, district manager, Leeds and Northrup Company, Cleveland, Ohio.
Maxwell L. Olsen, outside plant engineer, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Arthur F. W. Richards, consulting engineer, Richards and Bright, London, W.C.1, England.
Marion A. Savage, designing engineer, General Electric Company, Schenectady, N. Y.
Raymond F. Schierland, assistant engineer, Columbia Engineering Corporation, Cincinnati, Ohio.
Joseph K. H. Sticher, research engineer, The Detroit Edison Company, Detroit, Mich.
Daniel C. Vaughan, system protection engineer, Potomac Electric Power Company, Washington, D. C.
Stewart H. White, superintendent of utilities, City of Port Angeles, Wash.
John W. Wilson, assistant professor of electrical engineering, University of Florida, Gainesville.
Harry A. Winne, engineering, general department, General Electric Company, Schenectady, N. Y.
Richard B. Wright, engineer inspector, Consolidated Edison Company of N. Y., Inc., New York, N. Y.

24 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before August 31, 1939, or October 31, 1939, if the applicant resides outside of the United States or Canada:

United States and Canada

1. North Eastern

Brewer, N. M., Central New York Power Corporation, Utica, N. Y.
Parsons, R. J. (Member), Consolidated Car Heating Company, Albany, N. Y.
Stewart, C. J., Great Lakes Portland Cement Corporation, Buffalo, N. Y.

2. Middle Eastern

Caldwell, O. A., Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.
Liwschitz, M. (Member), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Pfeifer, A. A., North Electric Manufacturing Company, Galion, Ohio.

3. New York City

Eastman, H. L. (Member), Electric Advisers, Inc., New York, N. Y.

Fenton, A., Consolidated Edison Company of N. Y., Inc., New York, N. Y.

Palmer, A. P., 410 West 207 Street Corporation, New York, N. Y.

4. Southern

Heymann, A. P., 9 North Hyer Street, Orlando, Fla.

Trawick, H. P. (Member), Tallapoosa River Electric Membership Corporation, Lafayette, Ala.

5. Great Lakes

Egan, V. J., Commonwealth and Southern Corporation, Jackson, Mich.

Gaines, B., Fisher Body Company, Detroit, Mich.

Kallander, O. H. (Member), Care F. S. Haberly Consulting Engineer, Chicago, Ill.

Lyman, P. F., Commonwealth and Southern Corporation, Jackson, Mich.

Willey, R. E., Northwestern Bell Telephone Company, Minneapolis, Minn.

7. South West

Dunlap, L. B., Southwestern Bell Telephone Company, Dallas, Tex.

8. Pacific

Herz, S. V., 3317 Jackson Street, San Francisco, Calif.

Massey, J. T., Pacific Gas and Electric Company, San Francisco, Calif.

Nelson, M. R., General Cable Corporation, Los Angeles, Calif.

ReQua, R. L. (Member), City of San Francisco, San Francisco, Calif.

Total, United States—21

Elsewhere

Erskine, A., The Fife Electric Power Company, East Port, Dunfermline, Fife, Scotland.

Hollander, J. M. (Member), Electro-Mechanical Supplies, Ltd., Coventry, England.

Rush, J. P., Taikoo Sugar Refining Company, Hongkong, China.

Srikantaiya, D. S., Government of Mysore, Hole-Narsipur, Mysore State, India.

Starbuck, L. W. G. (Member), Walker Sons and Company, Ltd., Colombo, Ceylon.

Total, elsewhere—5

Engineering Literature

New Books in the Societies Library

Electrical engineers may be interested in the following new books, which are among those recently received at the Engineering Societies Library, New York, N. Y. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the preface of the book in question.

THE ECONOMICS OF BUSINESS ENTERPRISE. By W. Rautenstrauch. New York, John Wiley and Sons, 1939. 445 pages, diagrams, etc., 9 by 6 inches, cloth, $4.00. Aims to describe what is generally considered good practice in dealing with the economic problems of specific business enterprises, to inquire into the theories on which these practices rest, and to develop methods of analysis for the economic problems of a particular business. The final chapter treats in general of business enterprise on a national scale.

AIR CONDITIONING. By B. H. Jennings and S. R. Lewis. Scranton, Pa., International Textbook Company, 1939. 467 pages, illustrated, 9 by 6 inches, flexible, $4.00. The fundamentals of air conditioning are so presented as to form a working basis for the engineering student or the practicing engineer. The emphasis is on basic principles, although conventional methods of empirical treatment are given in some cases. Ordinary heating methods and refrigeration are considered at some length. Contains illustrative examples, problems, charts, and tables of data.

APPLIED ACOUSTICS. By H. F. Olson and F. Massa. Second edition. Philadelphia, Pa., P. Blakiston's Son and Company, 1939. 494 pages, illustrated, 9 by 6 inches, leather, $5.50. Presents information on the design, construction, operation, and analysis of modern microphones, loud speakers, and telephone receivers, emphasizing the electrical and mechanical aspects of electroacoustics. Acoustical measurements, testing methods, architectural acoustics, measurement of noise, and physiological acoustics are also considered.

VDI-JAHRBUCH 1939. Die Chronik der Technik. Edited by A. Leitner. Berlin, VDI-Verlag, 1939. 208 pages, 8 by 6 inches, paper, 3.50 rm. Containing over ninety reports by specialists, reviewing the literature on engineering published during 1938. About 10,000 references on all branches of engineering are included, with an extensive index.

ARC WELDING IN DESIGN, MANUFACTURE AND CONSTRUCTION. Cleveland, Ohio, James F. Lincoln Arc Welding Foundation, care of Lincoln Electric Company, 1939. 1408 pages, illustrated, 9 by 6 inches, leather, $1.50 in U.S.A.; $2.00 in other countries. A selection of 100 of the more than 400 papers which received awards from the James F. Lincoln Arc Welding Foundation, chosen from 44 sub-classifications. Some abridged. Subject index.

THE ELECTRIC POWER INDUSTRY: DEVELOPMENT, ORGANIZATION, AND PUBLIC POLICIES. By J. Bauer and N. Gold, with the technical co-operation of A. E. Shaw. New York and London, Harper and Brothers, 1939. 347 pages, tables, 10 by 6 inches, cloth, $3.50. A non-technical presentation of the public aspects of the industry for engineers, economists, and the general reader. Discusses the development and importance of the electric power industry, private organization and management, and problems of public policy and control. Selected bibliography.

AIR CONDITIONING, FUNDAMENTAL PRINCIPLES, PRACTICAL INSTALLATIONS AND OZONE FACTS. By E. W. Riesbeck. Second revised and enlarged edition. Chicago, Goodheart-Willcox Company, 1939. 443 pages, illustrated, 8 by 5 inches, flexible, $3.50. In a non-technical manner explains the principles of air conditioning; differentiates between conditioning and cooling; describes methods, equipment, installation, and adaptation, and shows how to figure requirements. Refrigeration, use of ozone, and water sterilization are treated as allied subjects.

ESSENTIALS OF ALTERNATING CURRENTS. By W. H. Timbie and H. H. Higbie. Second edition, rewritten. New York, John Wiley and Sons, 1939. 377 pages, illustrated, 8 by 5 inches, cloth, $2.25. Covers only information which the authors consider essential to the worker on a.c. appliances. The revised edition includes new devices and methods of using them and new applications of known devices. Current practice is now represented, as in the treatment of motors and control apparatus. Problems and numerical examples.

INDUSTRIAL ELECTRICITY. By J. M. Nadon and B. J. Celmine. New York, D. Van Nostrand Company, 1939. 607 pages, diagrams, etc., 9 by 6 inches, cloth, $3.00. Designed for those who intend to make a vocation of electrical work in industry. Contains the fundamental principles of electricity and magnetism, and considers their application to present-day equipment. More specialized topics include connecting methods and operating characteristics of electrical machines and controls, electronic devices, and electric welding.

INTRODUCTION TO CONTEMPORARY PHYSICS. By K. K. Darrow. Second edition. New York, D. Van Nostrand Company, 1939. 648 pages, illustrated, 9 by 6 inches, cloth, $7.00. Explains the principal recent advances in atomic and nuclear physics as fully as is consistent with mathematics not more difficult than the elements of wave-mechanics. Topics include the properties of elementary particles, the correlation of corpuscles and waves, the diffraction of electrons and X rays by crystals, the phenomena of ionization and excitation, the interpretation of spectra, wave mechanics, and the art and science of transmutation. The new edition is much expanded.

METER ENGINEERING. By J. L. Perna. Third edition. New York and Chicago, Pitman Publishing Corporation, 1938. 347 pages, illustrated, 8 by 5 inches, cloth, $3.75. Revised in accordance with recent developments, this book covers in detail the work connected with the installation, testing, and maintenance of electricity meters.

INDUSTRIAL ELECTRICITY, DIRECT-CURRENT PRACTICE. By W. H. Timbie. Second edition. New York, John Wiley and Sons, 1939. 635 pages, illustrated, 9 by 6 inches, cloth, $3.00. Written to meet the demand from technical schools for a textbook covering the important principles of electrical science as applied to modern industry. Explains how d-c electricity is generated, transmitted, and used, and affords a foundation for the study of the application of a-c electricity to present-day practice. Each chapter is followed by summary and problems.

NATIONAL PHYSICAL LABORATORY REPORT FOR THE YEAR 1938. London, His Majesty's Stationery Office, 1939. 147 pages, tables, 10 by 6 inches, paper (obtainable from British Library of Information, 50 Rockefeller Plaza, New York, $0.75). In addition to general information concerning the laboratory and its work, this publication presents the reports of the William Froude Naval Laboratory and the departments of physics, electricity, radio, metrology, engineering, metallurgy, and aerodynamics, indicating the state of the current researches.

PRINCIPLES AND PRACTICE OF RADIO SERVICING. By H. J. Hicks. New York and London, McGraw-Hill Book Company, 1939. 305 pages, diagrams, etc., 9 by 6 inches, cloth, $3.00. Written with a minimum of mathematics. Shows how to install, test, and repair radio receivers, giving step-by-step instructions in all the servicing procedures, and also a plain treatment of the necessary fundamental theory of electricity and radio.

TRANSACTIONS SECOND CONGRESS ON LARGE DAMS, 1936. Five volumes, edited by O. C. Merrill, International Commission on Large Dams of the World Power Conference. Washington, D. C., Superintendent of Documents, 1938. Volume I, 587 pages; Volume II, 406 pages; Volume III, 492 pages; Volume IV, 651 pages; Volume V, 492 pages., illustrated, 10 by 6 inches, cloth, $2.50 per volume; $10.00 per set of five volumes; 25 per cent discount for 100 volumes or more in a single order. These volumes contain a full report of the Washington, 1936, conference, including the papers presented, the round-table discussions, reports, and information concerning officers, organization, excursions, and other general matters. The questions considered by the conference were: special concrete; the interpenetrating of shrinkage, contraction, and expansion joints; the facing of masonry and concrete dams; geotechnical studies of foundation materials; and the calculation of the stability of earth dams. Other problems considered include: methods for insuring the safety of gravity dams; dams built of precast concrete blocks; dams built by depositing stone blocks in running water; prevention of "piping;" and silting of large reservoirs. Papers are in English, French, Spanish, or German, with summaries in all four languages.

DER ULTRASCHALL UND SEINE ANWENDUNG IN WISSENSCHAFT UND TECHNIK. By L. Bergmann. Second edition. Berlin, VDI-Verlag, 1939. 358 pages, illustrated, 8 by 6 inches, leather, 25 rm. Greatly enlarged second edition of a book intended as a broad survey of our knowledge of ultrasonics, with emphasis upon practical scientific and technical applications. Discusses the production and measurement of ultrasonic waves, and their uses in measuring the velocity and absorption of sound in various media and the elastic constants of solids, also their use in testing materials, in signaling, and in metallurgy and their chemical and physical effects. The bibliography has been extended.

WHO INVENTED THE TELEPHONE? By W. Aitkin. London and Glasgow, Blackie and Son, Ltd., 1939. 196 pages, diagrams, 8 by 5 inches, cloth, 5 s. This review of the history of the telephone consists largely of references to or extracts from technical literature. Much of the information on the early inventors and their claims has been gathered from contemporary documents.

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Transactions

Papers and Discussions Comprising Pages 371–434 of the 1939 Volume

Effect of Restriking on Recovery Voltage

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IT IS well known that when any portion of an electrical circuit is either opened or closed a transient condition will usually exist for some period, depending on the damping, before the circuit assumes its new steady state. In power circuits, such switching operations are the application and removal of faults or loads and the connecting or separating of various parts of a system. The transient conditions resulting from these switching operations give rise in some cases to overvoltages, which can be calculated by straightforward and more or less well-known methods, if the transient circuit parameters are known. However, in some instances voltages much higher than those predicted by such calculations have been obtained, and various explanations[1–9] have been offered for these occurrences.

In the present paper, it is suggested

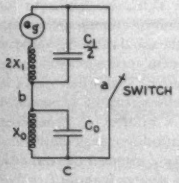

Figure 1

that some of these cases of excess voltage arise from the opening of a circuit which is already in a transient condition, the transient condition being caused by immediately preceding switching operations. For example, under certain circuit conditions they may arise from successive momentary clearings and re-establishments of a circuit at such short intervals as to allow comparatively little decay of the transients between these events. Under such conditions it is shown to be theoretically possible to build up extremely high voltages, although tests have indicated that the actual voltages realized are always less than the theoretical maximum.

General Analysis

This phenomenon may occur with circuits which may in the simplest case be reduced to that of figure 1. Here capacitance may exist also across the switch, but the only capacitance essential to the process is C_0, so all other capacitances will be neglected at this point. Generation may be either at the point shown or in the x_0 branch, without influencing the analysis except for the voltage b-c (that is, across x_0).

Let $2x_1$ be much less than x_0.

Now suppose that there is an arc at a which completes the circuit at this point. At each current zero there will be an attempt at extinction, and voltage will rise across the arc path either to complete the recovery transient and interrupt the circuit, or to cause a new breakdown of the arc path and re-establishment of the arc. If breakdown occurs, three components of current will flow; a resumption of the normal-frequency current, a d-c component, and an oscillation involving C_0, $2x_1$, and x_0. The frequency of this oscillation will usually be considerably greater than normal frequency. If it is very high the d-c component becomes very small and in the limit may be neglected without affecting the nature of the process to be described. The two remaining components initially have the same polarity, but in the second half-cycle of the natural-frequency component the polarities are opposite. Then if the restrike occurs at a sufficiently high point on the recovery transient and if $2x_1$ is considerably smaller than x_0, the instantaneous value of current in the natural-frequency component will exceed that of the normal-frequency component and the net current will tend to pass through zero. This gives an opportunity for a new attempt at interruption, which may result in a repetition of the process.

The manner in which this process may build up voltage is as follows, if generation

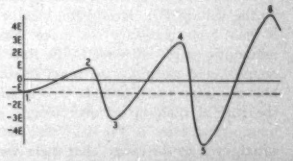

Figure 2. Build-up of voltage at point b of figure 1 due to successive clearings and restrikes within a normal half cycle

Odd-numbered points are clearings, even-numbered points restrikes. After clearing, voltage tends to oscillate about 0, after restrike it tends to oscillate about $-E$

is as shown in figure 1 and interruption occurs at the peak of a voltage wave.

It is evident from inspection that the steady-state voltage b-c is zero when the circuit is open at a, and substantially equal and opposite to the generated voltage when current is flowing at a. Therefore, if E is the generated voltage, which may be taken as equal to normal peak voltage, at the time of interruption the voltage b-c tends to change from $-E$ to 0; in doing so it will oscillate to $+E$. The first half cycle of this oscillation is given by the section between 1 and 2 of the curve of figure 2.

At this time the voltage at a is $2E$, and the arc may restrike. If it does, the voltage b-c tends to change from $+E$, to $-E$, and will therefore oscillate to $-3E$, as indicated by the section from 2 to 3 of the curve of figure 2.

At about the time when $-3E$ is reached, the net current may pass through zero and a second interruption may take place. The voltage b-c then starts to change from $-3E$ to zero, and may therefore oscillate to $+3E$, as from 3 to 4 of figure 2.

Paper number 39-50, recommended by the AIEE committees on power transmission and distribution, and protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted October 26, 1938; made available for preprinting December 20, 1938.

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1. For all numbered references, see list at end of paper.

The arc may then restrike again, and thus the process may repeat with a possible voltage increase of considerable magnitude at each repetition.

The voltage at *a* will, of course, go through changes somewhat similar to those of the voltage *b-c*.

This analysis has idealized the situation somewhat both as regards system performance by neglecting such items as the change in generated voltage, some of the effects of the presence of x_1, and decrement of the oscillations, and as regards performance of the arc by assuming restrike always to occur at the peak of the recovery transient.

A more exact treatment is given in appendix I, and from this are plotted the curves of figure 3, which apply to the voltage across the switch at *a* rather than to the voltage *b-c*. Even here, however, it has been necessary to make some assumption with reference to the time of restrike, and naturally the worst reasonable condition was assumed. As a result, the rate of build-up of overvoltages in most actual cases is less than that indicated, even to the extent that there may not be progressive build-up. Instead, successive voltages may be of a more or less random nature. Figure 4 shows an

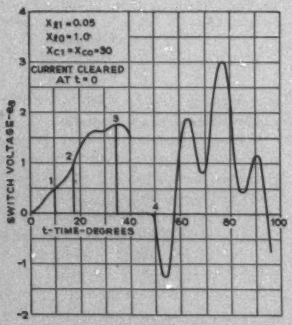

Figure 3. Switch voltage on interruption of circuits of figures 1 or 8

1—Restrike at e_{arc} = 0.5

2—Restrike at e_{arc} = 1.0

3—Restrike at e_{arc} = 1.77

4—Second clearing

oscillogram illustrating this phenomenon.

The circuit of figure 1, both with the capacitance $C_1/2$ connected as shown and with it connected directly across the breaker, may appear in the single-line diagram of various circuits quite common in operation. Any fault supplied from a rather extensive system through a small and more or less concentrated single reactance may act in this manner. This reactance may be a transformer or reactor, or even a short length of transmission line or cable. A few cases are on record in which overvoltages have been experienced which are believed to be attributable to this phenomenon but they do not appear to be nearly so widespread as the commonness of the circuit might lead one to expect.

Figure 4. Interruption of circuit of figure 1

Curve *A*—Voltage

Curve *B*—Current

Curve *C*—Breaker travel

Curve *D*—Trip-coil current

Certain other cases have individual features which are discussed hereinafter under the following headings:

1. Ground faults on systems grounded through neutral reactance.
2. Interruption of line charging current.
3. Arcing ground faults on systems with neutral isolated or grounded through reactance.

1. Ground Faults on Systems Grounded Through Neutral Reactance

It is obvious from inspection that the interruption of a single-line-to-ground fault on a system grounded through a neutral reactor fits the circuit of figure 1. Here x_0 represents the zero-phase-sequence reactance, which will lie for the most part in the neutral reactor; C_0 represents the zero-phase-sequence capacitance, or one-third of the capacitance of the entire system to ground. x_1 and C_1 represent positive-phase-sequence reactance and capacitance, respectively. Generation is as shown. In case of fault interruption there is a tendency for the restrike voltage to increase at successive current zeros because of the continually increasing separation of the contacts of the interrupting device. When this restrike voltage becomes sufficiently great, the resulting current oscillation may become so large as to pass through zero in its first cycle. The process of successive build-up of voltage may then take place as explained in the general analysis and illustrated in figure 2 for the neutral voltage and figure 3 for the voltage at the interrupting device.

The methods of appendix I have been used to investigate the conditions under which this type of build-up may occur and it has been found that they may be expressed in terms of the reactance x_0 of figure 1. A lower limit is fixed by the fact that extra current zeros do not occur when x_0 lies below the values indicated by the curves of figure 5, although it should be pointed out that even if x_0 is below these limiting values a voltage approaching three times normal peak may appear at the neutral, as indicated at point 3 of figure 2.

Two points are of interest on these curves. When C_1/C_0 is equal to or greater than unity, corresponding approximately to the usual cable or overhead transmission system, a conservative value of x_0 is ten times x_1; but when C_1/C_0 is equal to zero, which may be approached in the case of a number of generators which are substantially independent electrically except for a common neutral bus, x_0 should not be greater than four or five times x_1.

Once this lower limit is well passed, no great change takes place as a result of increase of x_0 until it approaches equality with the capacitive reactance C_0, that is, until the condition of the ground-fault neutralizer or Petersen coil is approached. The ground-fault current in a system grounded through a ground-fault neutralizer is largely in phase with the voltage, so that the recovery voltage is very small and consequently restriking is unlikely. Even with poor tuning, a cycle or more is required for voltage to recover to normal, so that there is little chance of a restrike at a voltage high enough to cause serious build-up by successive clearings and restrikes.

Beyond the ground-fault-neutralizer value, the natural frequency becomes lower than the operating frequency and the phenomenon becomes substantially that of the interruption of transmission-line charging current.

If it is desired to use a neutral impedance within the danger zone, successive restriking may still be prevented by the use of a parallel neutral resistor of proper value or by the use of a neutral resistor instead of a neutral reactor. The parallel neutral resistance must be low enough to prevent, by its damping action, the restrike current oscillation from passing through zero. Of course, in addition to this main accomplishment, it also reduces the initial recovery voltage, particularly for single-line-to-ground faults.

Calculations have shown that the required parallel resistance is always somewhat greater than that required for critical damping of the ground or zero-sequence circuit, the difference depending on the circuit natural frequencies and on the ratio of zero-sequence to positive-sequence reactance. It is therefore suggested that as a practical and conservative means of selecting the proper resistance, this critical damping value R_c be used. The value of this resistance is given approximately by

$$R_c = \frac{1}{2}\sqrt{x_{ln}x_{cn}}$$

where

R_c = shunt resistance required for critical damping

x_{ln} = inductive reactance of the ground circuit
= one-third of the zero-sequence inductive reactance for a three-phase system

x_{cn} = capacitive reactance of the ground circuit
= one-third of the zero-sequence capacitive reactance for a three-phase system

It may be seen from this equation that the power rating of the required resistor for a given neutral reactor is approximately proportional to the square root of the system capacity to ground.

The discussion above applies directly to single-line-to-ground faults on reactance-grounded systems. However, even in case of two- or three-phase faults to ground there is always a last phase to clear, and this may behave like a single-line-to-ground fault. Thus, the discussion applies qualitatively to all faults involving ground.

It is also evident that the neutral reactance under discussion may be that of a grounding transformer, rather than a reactor, without essentially changing the circuit conditions although in this case there may not be any conductor at neutral potential, so that the neutral may be eliminated as a possible breakdown point.

2. Interruption of Line Charging Current

Upon interruption of the charging current of a transmission line, cable, or

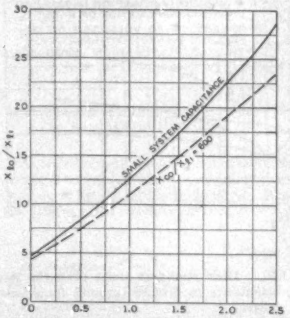

Figure 5. Critical ratio of zero-sequence reactance x_{l0} to positive-sequence reactance x_{l1}, as a function of ratio of positive-sequence capacitance C_1 to zero-sequence capacitance C_0—successive restriking may occur if x_{l0}/x_{l1} exceeds the critical value

capacitor at a current zero the rate of rise of recovery voltage is very slow. If, because of this fact, the circuit breaker interrupts at small contact separation and in addition has a relatively slow build-up of dielectric strength, the arc may restrike. When such restriking takes place, a current oscillation of large magnitude compared to the steady-state charging current occurs. This current may again be interrupted on its first zero, with a resulting recovery voltage which may be higher than normal. Continued restriking at successively higher voltages may take place in this case, just as in the case of the previous section, as the contact separation increases, until the final interruption is attained.

Such operation has been discussed in detail in references 8 and 9. An additional illustration is given in appendix II and figure 6, in order to show that the build-up of voltage may occur even with interruption of lumped capacitance current.

To prevent successive restriking it is desirable to build up the breaker dielectric strength as rapidly as possible after the first interruption and thus successfully prevent the first restrike.

Another method of attack is to introduce damping into the circuit by resistance in or across the breaker or line.

3. Arcing Ground Faults on Systems With Neutral Isolated or Grounded Through Reactance

A single-line-to-ground fault on an isolated-neutral system causes only a very small capacitance current to flow. Usually this current flows through an arc, which is interrupted at every current zero and requires a certain restrike voltage for reignition. The results of such action have been described for a particular case in references 1 and 7. A more or less constant restrike voltage may be expected, which limits the voltage on the faulted phase. The transient applied to the system at every such restrike and every subsequent clearing may lead to voltages in the unfaulted phases which in the steady state exceed the maximum transient voltages associated with simple application or interruption of a solid fault.

Curve *A* of figure 7 shows the maximum sustained voltages at the point of fault on the unfaulted phases of a three-phase system having a steady-state arcing ground on one phase. These voltages were obtained by tests on a miniature system.

For positive value of x_0/x_1 the curve of maximum obtainable voltage is affected considerably by the amount of system capacitance, the curve shown being the envelope of the many possible curves obtainable with particular values of capacitance.

It was found in test that if the restrike

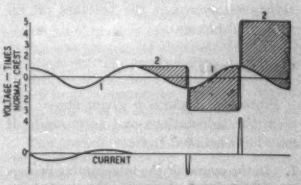

Figure 6. Interruption of capacitance current-circuit of figure 9

Curve 1—Voltage at inductance side of switch

Curve 2—Voltage at capacitance side of switch

Height of cross-hatched area gives voltage across switch

voltage was continually changing so that the phenomena were not periodic, the voltages on the unfaulted phase could be considerably increased. Such changes might be caused, in an arc to ground on a

power system, by wind or by changes in insulation characteristics.

For ready comparison, figure 7 shows also the steady-state fundamental voltage on the unfaulted phases during a solid

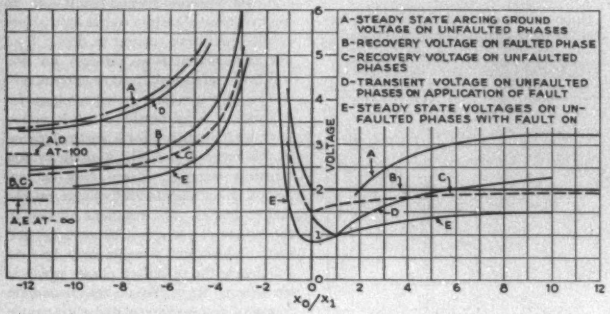

Figure 7. Single-line-to-ground fault on three-phase system—maximum voltages to ground at fault point in per unit of crest leg voltage before fault

jx_0 = zero-sequence impedance

jx_1 = positive-sequence impedance

line-to-ground fault (curve E) and the maximum transient voltage caused by the application (curve D) or removal (curves C and B) of such a fault. Resistance and arc drop are neglected in all curves except that for a sustained arcing ground (curve A). In general, fault resistance decreases the voltages on the unfaulted phases.

Conclusions

From the discussion given above and from the calculations and tests made, it may be concluded that:

1. In the course of the interrupting process on certain types of circuit, the current immediately following restriking of the arc after an early attempt to clear may involve high-frequency components of sufficient magnitude to cause the current to pass through zero very shortly after the restrike. Clearing at this time gives rise to voltages considerably in excess of those normally associated with the recovery transient.

2. Systems grounded through neutral reactors may be subject to these overvoltages.

3. If the possibility of these overvoltages is to be avoided, neutral-grounding reactors must satisfy one of the following conditions:

(A). Their reactance must be so low as to keep the zero-sequence reactance below

(a). Ten times positive-sequence reactance if the zero-sequence capacitance is no larger than the positive-sequence capacitance, or

(b). Five times positive-sequence reactance if the zero-sequence capacitance is much larger than the positive-sequence capacitance.

(B). Their reactance must tune the line capacitance to ground (ground fault neutralizer).

(C). They must be shunted by resistance to provide substantially critical damping.

4. The interruption of line charging current may give rise to high voltages unless restriking is prevented either by quick clearing by means of rapid build-up of dielectric strength in the circuit breaker, or by circuit damping.

Appendix I

In this appendix there is presented an approximate analysis of the behavior of a three-phase power system with neutral reactance grounding, during the clearing of a single-line-to-ground fault and with restriking of the arc after the first clearing. The system may be approximately represented by the circuit of figure 8, which in turn may be represented for the purposes of analyzing a single-line-to-ground fault by the circuit of figure 1.

It is assumed that:

1. Arc drop is zero.
2. All resistances are zero.
3. Arc interruption occurs only at current zeros determined by the circuit constants.
4. The arc restrikes at various values of switch voltage.
5. Positive- and negative-sequence impedances are equal.

Under these conditions the fault current before interruption is given by the equation

$$i_{a1} = \frac{\sin t}{Z_{0s} + 2Z_{1s}} = I_a \sin t \qquad (1)$$

where

x_{c1} = positive-sequence capacitive reactance

x_{l1} = positive-sequence inductive reactance

Z_{0s} = steady-state zero-sequence impedance

$$Z_{0s} = \frac{x_{c0}x_{l0}}{x_{c0} - x_{l0}}$$

The normal voltage at the fault point is 1.0

Z_{1s} = steady-state positive-sequence impedance

$$Z_{1s} = \frac{x_{c1}x_{l1}}{x_{c1} - x_{l1}}$$

t = time measured from the instant the current is interrupted

x_{c0} = zero-sequence capacitive reactance

x_{l0} = zero-sequence inductive reactance

After the current is interrupted at $t = 0$, the recovery voltage on the faulted phase is

$$e_{a1} = I_a Z_{0s} (\cos t - \cos \omega_0 t) + 2I_a Z_{1s} (\cos t - \cos \omega_1 t) \qquad (2)$$

or

$$e_{a1} = \cos t - I_a Z_{0s} \cos \omega_0 t - 2I_a Z_{1s} \cos \omega_1 t$$

where

I_a is defined by equation 1

ω_0 = zero-sequence natural frequency

$\omega_0 = \sqrt{x_{c0}/x_{l0}}$

ω_1 = positive-sequence natural frequency

$\omega_1 = \sqrt{x_{c1}/x_{l1}}$

The zero-sequence voltage is

$$e_{a1} = I_a Z_{0s} \cos \omega_0 t \qquad (3)$$

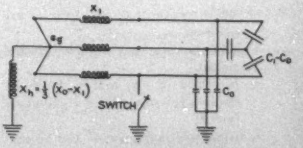

Figure 8. Typical three-phase system with single-line-to-ground fault

If restrike occurs at time $t = t_1$, the restrike current is

$$i_{a2} = -\frac{\sin t_1}{x_{l0} + 2x_{l1}} + \frac{I_a}{x_{l0} + 2x_{l1}} \times \left(\frac{Z_{0s}}{\omega_0} \sin \omega_0 t_1 + \frac{2Z_{1s}}{\omega_1} \sin \omega_1 t_1\right) + I_a \sin (t + t_1) + \frac{(\omega'^2 - \omega_0^2)(\omega_1^2 - \omega'^2)}{(x_{c0} + 2x_{c1})(\omega'^2 - 1)\omega'^2} \times [\sin t_1 \cos \omega' t + \omega' \cos t_1 \sin \omega' t] + \frac{I_a}{(x_{c0} + 2x_{c1})\omega'^2} [2Z_{1s}(\omega'^2 - \omega_0^2)(\omega_1 \sin \omega_1 t_1 \times \cos \omega' t + \omega' \cos \omega_1 t_1 \sin \omega' t) - Z_{0s}(\omega_1^2 - \omega'^2)(\omega_0 \sin \omega_0 t_1 \cos \omega' t + \omega' \cos \omega_0 t_1 \sin \omega' t)] \qquad (4)$$

or

$$i_{a2} = I_0 + I_a \sin (t + t_1) + I_n \cos (\omega' t - \theta_n)$$

where

t is now measured from the point at which restrike occurred

t (equation 4) $= t$ (equation 2) $- t_1$

ω' = natural frequency with fault on

$$\omega' = \sqrt{\frac{(x_{l0} + 2x_{l1})x_{c0}x_{c1}}{(x_{c0} + 2x_{c1})x_{l0}x_{l1}}}$$

I_0, I_n, and θ_n are defined by equation 4

While this restrike current is flowing, the zero-sequence voltage is

$$e_{02} = Z_{02}I_0 \cos(t + t_1) - \frac{x_{c0}(\omega_1^2 - \omega'^2)}{(x_{c0} + 2x_{c1})(\omega'^2 - 1)\omega'}[-\sin t_1 \sin \omega' t + \omega' \cos t_1 \cos \omega' t_1] + \frac{x_{c0}I_0}{(x_{c0} + 2x_{c1})\omega'} \times [-2Z_{12}(-\omega_1 \sin \omega_1 t_1 \sin \omega' t + \omega' \cos \omega_1 t_1 \cos \omega' t_1) + \frac{Z_{02}(\omega_1^2 - \omega'^2)}{(\omega'^2 - \omega_0^2)} \times (-\omega_0 \sin \omega_0 t_1 \sin \omega' t + \omega' \cos \omega_0 t_1 \cos \omega' t_1)] \quad (5)$$

or

$$e_{02} = Z_{02}I_0 \cos(t + t_1) + \frac{x_{c0}\omega' I_n}{\omega'^2 - \omega_0^2} \sin(\omega' t - \theta_n)$$

Note that $\left(\frac{jx_{c0}\omega'}{\omega_0^2 - \omega'^2}\right)$ is simply the impedance of the zero sequence circuit at a frequency ω'.

If the current given by equation 4 passes through zero at $t = t_2$, where t is measured from time t_1, the circuit may then be recleared. After this second clearing the recovery voltage on the faulted phase is

$$e_{a2} = \cos(t + t_1 + t_2) + \omega_0 I_0 x_{l0} \sin \omega_0 t + \omega_1 2I_0 x_{l1} \sin \omega_1 t - I_a Z_{02}[\cos(t_1 + t_2) \times \cos \omega_0 t + \omega_0 \sin(t_1 + t_2) \sin \omega_0 t] - 2I_a Z_{12}[\cos(t_1 + t_2) \cos \omega_1 t - \omega_1 \sin(t_1 + t_2) \sin \omega_1 t] - \frac{I_n x_{c0}}{\omega'^2 - \omega_0^2} \times [\omega_0 \cos(\omega' t_2 - \theta_n) \sin \omega_0 t + \omega' \sin(\omega' t_2 - \theta_n) \cos \omega_0 t] + \frac{2I_n x_{c1}}{\omega_1^2 - \omega'^2} [\omega_1 \cos(\omega' t_2 - \theta_n) \sin \omega_1 t + \omega' \sin(\omega' t_2 - \theta_n) \cos \omega_1 t] \quad (6)$$

where

t (equation 6) $= t$ (equation 4) $- t_2$

$= t$ (equation 2) $- t_1 - t_2$

$$\frac{x_{c0}}{\omega'^2 - \omega_0} = \frac{2x_{c1}}{\omega_1^2 - \omega'^2} = \frac{x_{c0} + 2x_{c1}}{\omega_1^2 - \omega_0^2}$$

The zero-sequence voltage is the negative of the sum of all the terms of equation 6 having a frequency ω_0.

As an example of the application of these equations, a circuit with $x_{l0}/x_{l1} = 20$, $x_{c0}/x_{l0} = 30$, and $x_{c1} = x_{c0}$ has been considered. Figure 3 shows the recovery voltage on the faulted phase. If restrike occurs at half or normal voltage (points 1 and 2), the resulting oscillations of the restrike current do not pass through zero and the current continues for another half cycle; if restrike occurs at maximum recovery voltage (point 3), the restrike current oscillates to zero at point 4 and is there interrupted. The recovery voltage then rises to about three times normal, if no further restriking occurs. At the same time the zero-sequence voltage (which is nearly equal to the neutral voltage to ground) rises to about two times leg voltage.

By means of these equations and tests on miniature circuits with $x_{c1} = x_{c0}$, it has been determined that if $x_{l0}/x_{l1} < 10$, the restrike current cannot oscillate to zero regardless of the point of restrike. Therefore a second (or more) clearing is rendered impossible.

If $x_{c1} > x_{c0}$ the critical value of x_{l0}/x_{l1} is decreased, while if $x_{c1} < x_{c0}$, the critical x_{l0}/x_{l1} is increased, as shown by figure 5.

Appendix II

As an extremely simplified representation of the interruption of charging current one may consider the circuit of figure 9. Here the line or other capacitance is represented

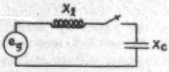

Figure 9

by a lumped capacitance x_c supplied through the source inductance x_l. If this circuit is interrupted at a current zero the recovery voltage in per unit of normal voltage at the capacitor is

$$e_{a_1} = \frac{x_c - x_l}{x_c} \cos t - 1 \quad (7)$$

If restriking takes place when the recovery voltage is maximum at $t = \pi$, the restrike current is

$$i_{a2} = \frac{\sin t - 2\omega \sin \omega t}{x_c} \quad (8)$$

where t is now measured from the instant of restrike, and

$$\omega = \sqrt{x_c/x_l}$$

It is evident that in general the natural-frequency component of i_{a2} is much greater than the fundamental component. Thus a large current oscillation of high frequency takes place and may be interrupted at its first current zero. If this occurs, the restrike current and subsequent recovery voltage, neglecting minor oscillations, will appear as in figure 6. By continuing the process begun by equations 7 and 8 we arrive at the successively higher voltages of figure 6.

It is not to be inferred that voltages of exactly this character exist. Instead, there is here also a randomness in the restrike voltage at successive intervals which largely controls the individual voltage peaks. In addition, the capacitance may be distributed along a transmission line as in references 8 and 9, and the voltage may also be affected by coupling between phases of a polyphase system. However, the tendency and the possibility of a building up of high voltages is clearly shown, so that it seems highly desirable to prevent such restriking.

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Discussion

R. A. Hentz (Philadelphia Electric Company, Philadelphia, Pa.): From the time impedances in the neutrals of generators were deemed desirable, resistances were used almost exclusively, if not entirely so, and to the best of my knowledge with complete satisfaction as far as electrical characteristics are concerned. Later grounding reactors instead of resistors were used in a number of cases, as they offered the advantages of smaller space, less cost, and of being less subject to deterioration. With the advent of transmission substations where the busses were supplied from delta-connected transformer banks, neutral grounding was obtained in many cases by means of zigzag grounding transformers.

The analysis made by the authors brings out (conclusion number 2) that systems grounded through neutral reactors may be subject to overvoltages considerably in excess of those normally associated with the recovery transient. This analysis is of considerable importance to those systems which use neutral reactors or where grounding transformers are employed which resulted in a somewhat similar electrical condition.

The importance of the subject is further emphasized by the fact that not only can difficulties result from neutral grounding through reactance, but that breakdowns have occurred both to machines and cables on systems for which this form of grounding gives a probable explanation.

Reactance grounding can be eliminated relatively easily where "wye"-connected machines or other equipment are employed by installing neutral resistors in place of the

reactances. This in my opinion is to be preferred to paralleling the existing reactors with a resistor. The situation is not so simple where the grounding transformers are employed. Such situations, therefore, present a challenge to designing engineers for the development of some equipment which will either replace or supplement these grounding transformers to the end that these dangerous overvoltages may be reduced to safe limits.

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper represents a valuable addition to the literature on voltage recovery transients. It will be noted that it contains actual test data substantiating at least the order of magnitude of the overvoltage due to an arcing ground predicted by Messrs. R. D. Evans, A. C. Monteith, and R. L. Witzke (AIEE TRANSACTIONS, volume 58, 1939, pages 386–97). The phenomena, however, consisted of more restrikes under less severe conditions than those postulated by Messrs. Evans, Monteith, and Witzke, so it is not certain that the apparent confirmation is more than an accident.

J. A. Adams (Philadelphia Electric Company, Philadelphia, Pa.): It is of interest to compare the limits of zero-sequence reactance given in conclusion 3 with values which have existed during faults on actual systems where the phenomena discussed have probably been the cause of secondary failures.

In two frequency-converter substations on the Philadelphia Electric Company system the neutrals of the 25-cycle generators were grounded through four-ohm reactors. While operating one of these substations with two generators connected to the 13.2-kv bus, one generator with the neutral grounded through the reactor and the other with the neutral ungrounded, a single-phase-to-ground fault developed on one of the cables fed from the bus. After the fault was cleared it was found that the neutral lead on the generator with its neutral ungrounded had broken down to ground. In this case the ratio of x_0/x_1 was 25.7, which is well above either of the lower limits given. For another fault on this system with only one generator operating the ratio of x_0/x_1 was 12.9 and a second breakdown did not occur. The ratio of C_1/C_0 for these two cases is estimated to be approximately unity.

At the other substation practically simultaneous faults developed to ground on one phase of the leads from one generator operating with its neutral grounded through the reactor and in the winding in the same phase of the second generator operating with its neutral ungrounded. In this case the ratio x_0/x_1 was 14.6 and the ratio of C_1/C_0 was approximately unity. At another time, however, a cable failure to ground with the same system set up did not cause a second breakdown, probably indicating that this ratio of x_0/x_1 is near the critical value.

As a result of an analysis of these cases of trouble, the neutral-grounding reactors are being replaced with four-ohm resistors.

R. D. Evans, A. C. Monteith, and R. L. Witzke (all of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Considering the paper by Messrs. Concordia and Skeats, we feel that it is essential to consider the arc voltage and the increase in voltage due to extinction of the arc prior to a normal current zero as this effect will give rise to higher voltages than indicated in their paper. This is of particular interest when considering grounding means for generators as the extinction voltage may be comparable to the normal line-to-neutral voltage and proportionately increase the transient voltages.

(See also discussion, page 412.)

C. Concordia and W. F. Skeats: The authors are particularly grateful to those discussers who have contributed their experience with overvoltages apparently coming within the scope of this paper. Circuits falling within the general classification susceptible to this type of overvoltage appear to be more widespread than is indicated by any trouble experience, and a study of trouble experience seems to afford the most practical means of setting down more precisely the conditions under which overvoltages may be expected. In this connection it should be noted that fundamentally the phenomenon is not limited to systems using neutral-grounding reactors but may occur on any system where, looking back from the point of fault, one sees first a small reactance, then an appreciable capacitance, and finally a comparatively large reactance.

High arc voltage preceding current zero tends to increase the voltage reached on the normal recovery transient, which indirectly increases the likelihood, upon restrike, of a high-frequency current oscillation of sufficient amplitude to cause the total current to pass through zero early in the cycle and so start the process of building up voltage. High arc voltage after a restrike also helps directly to bring about such an early current zero. However, once the build-up process has been started, the effect of arc voltage may be to retard the rate of build-up and limit the final voltage obtained rather than the reverse. Thus the authors cannot agree with the contention of Messrs. Evans, Monteith, and Witzke that arc voltage of reasonable value will greatly increase the voltages reached by the build-up process discussed in the paper, although of course, extremely high arc voltages may result in dangerously high recovery voltages even without this build-up process. In presenting their paper the authors felt that the overvoltages arising from successive restriking with certain critical circuit constants should be separated from those arising from high arc voltage.

The elimination of trouble in the case of zigzag grounding transformers may be accomplished either by using a grounding transformer whose reactance satisfies the conditions of conclusion 3*A* or 3*B*, or by using sufficient series resistance between the transformer neutral and ground, although this last remedy might in some cases reduce the ground currents too much for proper relaying.

Overvoltages During Power-System Faults

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OVERVOLTAGES may be produced by lightning, switching surges, faults, both solid and arcing, and the overspeeding of machines due to loss of load. The effect of circuit and machine characteristics on the duration and magnitude of these overvoltages has received considerable attention.[1–10] Furthermore, field tests have been made in order to determine the effectiveness of different methods of grounding, and the accuracy of the methods used to calculate the magnitude of overvoltage during system faults.[11–13]

It seems to be the proper time to consider and review the overvoltages produced by the occurrence of system faults, in order that full advantage of present-day knowledge may be taken by those concerned with system design and operation.

There are essentially three components of voltage due to the occurrence of a system fault:

1. Fundamental-frequency voltages.

2. Natural-frequency voltages usually of short duration which are superimposed upon the fundamental-frequency voltages.

3. Harmonic voltages resulting from unbalanced currents flowing in rotating machines in which the reactances in the direct and quadrature axes are unequal.

In general, protective devices, particularly lightning arresters, must be capable of withstanding the transient overvoltages to which they may be subjected for periods of short duration, and then must be able to seal off the power follow current associated with the sustained voltages. Unnecessary lightning-arrester failures due to excessive sustained overvoltages during fault may be prevented by properly grounding and operating the system.

It is the fundamental-frequency overvoltages which largely determine the lightning-arrester rating and the corresponding insulation protective levels. These in turn are a factor in determining the allowable apparatus insulation levels. From a technical standpoint, the fundamental-frequency voltages can be determined with fair accuracy.

Although this phase of the subject is of considerable importance, it has been discussed in the literature only in somewhat scattered and incomplete form. It is the purpose of this paper to review and analyze the factors which determine the maximum voltages which may be obtained on a system following the occurrence of faults, so that a more rational selection of system protective equipment can be made and the best method of system grounding determined.

Results of calculations, and of tests on a miniature system are presented. Included in these results are the transient voltages as well as the fundamental-frequency voltages that occur on a system during a fault. The information on transient overvoltages is of value in indicating the maximum magnitude of voltage that may be obtained on a system during a solid fault, thus showing the magnitude of transient voltage which is inherent in the circuit and which cannot be reduced by the elimination of excess voltages due to switching or arcing, or by building lightning-proof lines. Furthermore, as it seems reasonable to assume that arcing at the fault may subject the circuit during the arcing period to voltages of the same order of magnitude as those obtained immediately subsequent to the initial application of the fault, the curves presented can be used as a guide to indicate the maximum voltage which may be expected due to arcing across an insulator.

The paper analyzes the effect of those factors which determine the magnitude of the overvoltages during faults, which are the most common causes of high sustained voltages. A study of these voltages is usually a necessary first step, after which refinements and the more unusual cases can be considered. The effect of different methods of grounding and the influence of fault and arc resistance are included.

Conclusions

From the results discussed in this paper, the following conclusions can be drawn:

1. Line-to-ground faults for most systems can be used as a basis for determining the maximum fundamental-frequency and transient voltages during faults.

2. If a system is solidly grounded or grounded through reactance, so that the resultant zero-sequence impedance viewed from the fault is inductive rather than capacitive, the fundamental-frequency voltages-to-ground on the unfaulted phases at the fault will not be greater than 1.73 times normal line-to-neutral voltage.

3. If a system is grounded through resistance, so that the resultant zero-sequence impedance viewed from the fault is inductive rather than capacitive, the fundamental-frequency voltages-to-ground of the unfaulted phases at the fault will always be less than twice normal line-to-neutral voltage.

4. In order that the overvoltages during faults shall not exceed that which is considered safe for the operation of grounded-neutral lightning arresters, it is advisable that careful attention be paid to the method of grounding and the number of grounding points in the system. Consideration should also be given to the possibility of temporary disconnection of these grounding points and the resulting overvoltages which may occur.

5. Isolated-neutral systems may be subjected to particularly high overvoltages if the system is large in extent. The overvoltages at or near the region of resonance are appreciably reduced by fault and line resistance. This may be an important factor, particularly in low-voltage systems. On the other hand, resistance in the fault or ground return for a grounded-neutral system may slightly increase the overvoltages obtained on one of the open phases.

6. The transient overvoltages obtainable on a system which ordinarily might be considered to be solidly grounded may approach 2.73 times normal. Sustained voltages are generally higher for systems grounded through resistance than for systems grounded through corresponding values of reactance. The natural-frequency transient voltages obtained on a system grounded through resistance are practically negligible except when the resistance is high relative to the positive-sequence reactance.

7. The transient overvoltages during faults are not expected to be of sufficient magnitude to cause breakdown of the major insulation provided it is in good condition, except for the case of an isolated-neutral system having an appreciable amount of line or cable capacity to ground. The overvoltages during faults in a grounded-neutral system are not as great in magnitude as those which may be expected from lightning or switching surges.

8. Ground-fault-neutralizer (Petersen coil) systems are subjected to transient and fundamental-frequency overvoltages which are, in general, higher than those of a solidly grounded system but lower than the volt-

Paper number 39-52, recommended by the AIEE committees on power transmission and distribution, and protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted November 12, 1938; made available for preprinting December 28, 1938.

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1. For all numbered references, see list at end of paper.

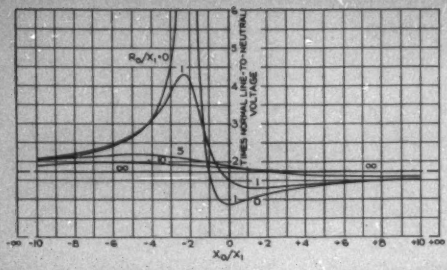


Figure 1. Fundamental-frequency voltages. Line-to-ground fault. Maximum voltage-to-ground of unfaulted phases at the fault

$$Z_1 = Z_2 = 0 + jX_1$$
$$Z_0 = R_0 + jX_0$$
$$R_f = 0$$

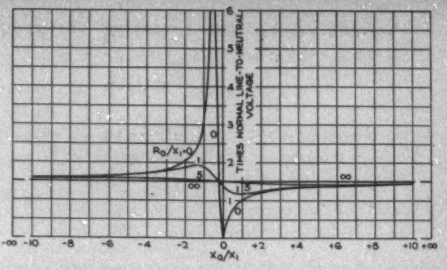


Figure 2. Fundamental-frequency voltages Double-line-to-ground fault. Voltage-to-ground of unfaulted phase at the fault

$$Z_1 = Z_2 = 0 + jX_1$$
$$Z_0 = R_0 + jX_0$$
$$R_f = 0$$

ages which can occur on an isolated-neutral system.

Basis of Study

The calculations, and tests on a miniature system, made to determine the magnitude of overvoltage following the occurrence of system faults, were based on the following assumptions and considerations:

1. The fault is a solid fault; that is, there is no arcing. Arcing tends to subject the circuit to a more or less continuous transient condition. It has been shown that very high voltage may be obtained in a circuit with no losses under assumed conditions of arc interruption and restriking.[7,14] Evidence indicates that these mechanisms of arcing do not ordinarily occur at the point of fault,[13,15] although such phenomena may be associated with switch operation.[15] It is believed that the maximum voltage which may be expected due to arcing can be taken to be approximately that corresponding to the transient overvoltage obtained immediately following the occurrence of a solid fault. Under this assumption the transient voltages presented in the paper are an indication of the maximum voltage which may be obtained due to arcing at the fault.[15]

2. Only fundamental and natural-frequency components of voltage are considered. Harmonics produced by the saliency effect of rotating apparatus are neglected. This assumes in effect that $x_0''/x_d'' = 1$. Exceptionally high voltages may occur due to saliency effects, particularly for the case of water-wheel generators not equipped with amortisseur windings and disconnected from their load. These overvoltages tend to be increased if the generator is left connected with an unbalanced fault to an appreciable amount of transmission line or cable so as to form a capacitive load. The conditions for this important exception are usually evident and are discussed fully in two recent papers.[5,8]

It is important to realize, however, that a certain amount of distortion due to this effect may occur for many system faults and that this will tend to increase the sustained voltages above those based only upon a consideration of the fundamental-frequency components.

3. Sudden disconnection of load and overspeeding of the system and connected generators is not considered. Loss of load on a generator may result in overvoltages due both to the sudden disconnection of the load and also to the overspeeding.[4] The results presented in this paper can, of course, be modified in order to indicate the increase in voltage which might be obtained under these conditions. This effect is most pronounced in portions of the system which overspeed due to loss of load on nearby hydro stations.

4. Negative-sequence impedances are assumed equal to positive-sequence impedances. The effect of rotating loads and machines, except in the case of synchronous machines not equipped with amortisseur windings, is to make the negative-sequence impedance less than the positive and to increase the losses with fault duration. These effects, in general, tend to reduce the magnitude of overvoltage calculated with equal positive- and negative-sequence impedances.

5. The magnitude of the positive-sequence impedance is assumed to be constant for the period in which the overvoltage is being determined. As the effective impedance of a rotating machine changes with time, it is necessary to consider the impedance under conditions which may result in the greatest overvoltage. On an isolated system, for example, the greatest overvoltage may be obtained based on impedances corresponding to the synchronous condition rather than the subtransient or transient condition. Because these impedances vary with time after the fault occurs, it is desirable that results be presented in the form of curves so that the range of voltage can be easily determined.

6. The effects of saturation and corona are not included. Both would tend to reduce

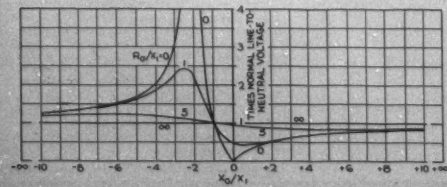


Figure 3. Fundamental-frequency voltages. Line-to-ground fault. Zero-sequence voltage at the fault

$$Z_1 = Z_2 = 0 + jX_1$$
$$Z_0 = R_0 + jX_0$$
$$R_f = 0$$

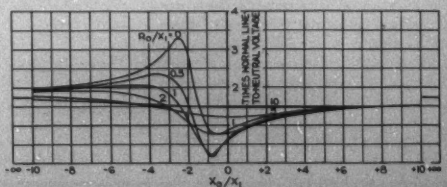


Figure 4. Fundamental-frequency voltages. Line-to-ground fault on phase a. Phase b voltage-to-ground at the fault

$$Z_1 = Z_2 = R_1 + jX_1$$
$$Z_0 = R_0 + jX_0$$
$$R_f = 0$$
$$R_1/X_1 = 0.4$$

the magnitude of overvoltage. The error in neglecting these factors, in general, increases with increase in the magnitude of overvoltage. In the region of resonance, saturation is an important factor in limiting the excessive fundamental-frequency overvoltages.

7. Overvoltages caused by unusual system conditions are neglected. For example, nonlinear circuit instability may be produced as a result of the opening of fuses or single-pole disconnect switches, thereby causing the magnetizing currents of potential or power transformers to flow through line capacitance with resulting overvoltages.

8. The miniature system used for determining transient overvoltages was set up to represent a low-loss system; that is, the ratio of r_1/x_1 was approximately 0.03. For systems having higher losses, the transient overvoltages will be somewhat less because of greater decrement factors.

9. Tests on the miniature system for determination of maximum transient voltage were made by representing the system by lumped impedance elements. This will, in general, lead to higher transient overvoltages at the point of fault than will be obtained in an actual system. This pessimistic result is due to the fact that the number of circuit natural frequencies is less than that on an actual system, and the resultant transient voltages are therefore likely to be of greater magnitude.

Discussion of Results

Fundamental-Frequency Voltages

Based on the foregoing assumptions, figure 1 gives the maximum fundamental-frequency voltage to ground which will occur on either of the unfaulted phases at the point of fault following a line-to-ground fault. Positive- and negative-sequence resistances are neglected, but zero-sequence resistance is included. Fault resistance is neglected. Figure 1 has an abscissa of X_0/X_1, where $Z_1 = 0 + jX_1$ and $Z_0 = R_0 + jX_0$ are the positive- and zero-sequence impedances, respectively, viewed from the fault. X_0 may be positive or negative. See equations 10 and 11, appendix A.

Figure 2, similar to figure 1, gives the maximum fundamental-frequency voltage on the unfaulted phase at the point of fault following a double-line-to-ground fault. Fault resistance and positive- and negative-sequence resistances are neglected. See equation 13, appendix A.

Figure 3 gives the zero-sequence voltage at the point of fault for a line-to-ground fault under the conditions of figure 1. The zero-sequence voltage at the point of fault for a double-line-to-ground fault under the conditions of figure 2, is one-third the voltage on the unfaulted phase given by figure 2. See equations 9 and 12, appendix A.

For a system which has its neutrals solidly grounded or grounded through reactance, the ratio X_0/X_1 will ordinarily be positive. That is, the zero-sequence impedance viewed from the fault is inductive rather than capacitive in effect. With neutrals grounded through resistance, X_0/X_1 may be either positive or negative. For an isolated-neutral system X_0/X_1 is negative. Also in a system which is extensive in number of miles of connected line or cable compared with the total admittance of the grounded points, the ratio of X_0/X_1 may be negative. With X_0/X_1 negative, the voltages obtained correspond to those on the left-hand side of the vertical axis. Under this condition, it is possible to obtain high overvoltages, particularly for small values of R_0/X_1 and values of X_0/X_1 in the region of resonance.

With all resistance neglected, infinite fault currents and voltages will occur if $X_0/X_1 = -2$ for a line-to-ground fault, and -0.5 for a double-line-to-ground fault. See appendix A, equations 9–13. Values of X_0/X_1 in the neighborhood of -2 or -0.5 are considered to be in the resonance region. Operation in the region of resonance with a small ratio of R_0/X_1 is expected to be unusual, and undoubtedly will occur only for isolated-neutral systems or grounded systems following the loss of the system ground point.

Figures 4 and 5, similar to figure 1, show the overvoltages which may be obtained on phases b and c, respectively, at the point of fault for the case of a single-conductor-to-ground fault on phase a. These two curves apply for $R_1/X_1 = 0.4$. Other curves similar to these have been prepared for early publication by E. M. Hunter with different ratios of positive-sequence resistance to reactance. This particular case is selected as being representative. As will be noted from these curves, the voltages on phase c are, in general, higher than those on phase b, although this is not true for all ratios of R_0/X_1 and X_0/X_1.

Figure 6, for the line-to-ground fault, shows the effect of fault resistance. Resistance except in the fault is neglected. As R_f/X_1 is increased from zero to $R_f/X_1 = 1$, approximately, the voltage of one of the unfaulted phases is increased and the other decreased, except in the region of resonance where both are decreased. The curve for $R_f/X_1 = 1$ is given in figure 6. As R_f/X_1 is further increased, the voltages decrease. Any increase in fault resistance decreases the overvoltage obtained in the region of resonance.

R_0 includes the effect of resistance in the ground return and in the neutral, while R_f of figure 6 is the resistance in the arc or fault. Figures 1, 2, 4, and 5 can be used to determine the magnitude of the fundamental-frequency fault voltages of systems with isolated neutral, neutral solidly grounded or grounded through resistance, reactance, or impedance. Z_0

Figure 5. Fundamental-frequency voltages. Line-to-ground fault on phase a. Phase c voltage-to-ground at the fault

$Z_1 = Z_2 = R_1 + jX_1$
$Z_0 = R_0 + jX_0$
$R_f = 0$
$R_1/X_1 = 0.4$

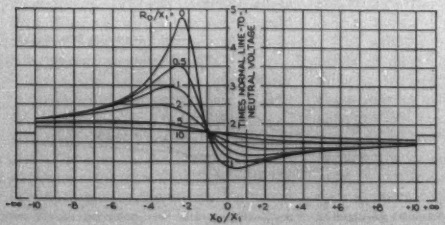
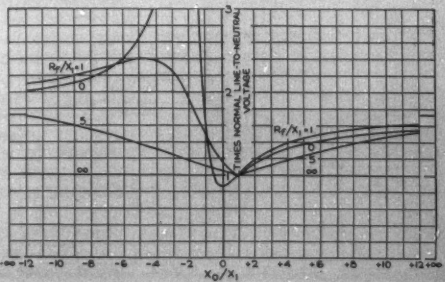


Figure 6. Fundamental-frequency voltages. Line-to-ground fault. Maximum voltage-to-ground of unfaulted phases at fault

$Z_1 = Z_2 = 0 + jX_1$
$Z_0 = 0 + jX_0$



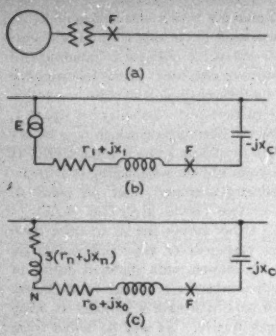


Figure 7

(a)—One-line diagram of power system consisting of synchronous machine, transformer bank, and transmission line

(b)—Approximate positive-sequence fundamental-frequency impedance diagram

(c)—Approximate zero-sequence fundamental-frequency impedance diagram

$= R_0 + jX_0$ is the zero-sequence impedance viewed from the fault and therefore includes the effect of neutral impedance.

Comparing corresponding curves in figures 1 and 2, it is seen that for the same system and fault location, that is, same values of X_0/X_1 and R_0/X_1, higher voltages are obtained for the line-to-ground than for the double-line-to-ground fault, except for the $R_0/X_1 = 0$ curve when X_0/X_1 lies between 1 and 5 and between -0.2 and -1.2, approximately. With X_0/X_1 between 1 and 5, and $R_0/X_1 = 0$, the voltages for the line-to-ground fault are but slightly less than those for the double-line-to-ground fault. As R_0/X_1 is increased, voltages increase more rapidly for the line-to-ground fault than for the double-line-to-ground fault. With $R_0/X_1 = 1$, higher values for the line-to-ground fault than for the double-line-to-ground fault are obtained. From equation 13, appendix A, any increase in R_1 reduces the voltage on the unfaulted phase for the double-line-to-ground fault; also, any increase in R_f reduces the voltage except when X_0/X_1 lies between -0.2 and 1.0.

Since resistance is always present, it can be concluded that with $Z_1 = Z_2$, the maximum fundamental-frequency voltage at the fault for the line-to-ground fault is as great as, or greater than, that for the double-line-to-ground fault, except for values of X_0/X_1 between -0.2 and -1.2, and very little resistance in the system. This represents a condition that is not expected to be met in practice except under the most unusual conditions.

Transient Voltages

Transient voltages here include both the fundamental-frequency component of voltage and the natural-frequency components. Curves for transient voltages following faults in terms of system impedances viewed from the fault cannot be drawn for the general case, as has been done for fundamental-frequency voltages. In the actual system, the transient voltages are affected by the number, connection, and arrangement of the circuits. To simplify the work, and give an indication of the maximum transient voltage to be expected, a system consisting of a synchronous generator, transformer bank, and transmission line open at the distant end was considered. With the fault on the line near the transformer terminals, as a first approximation, the open transmission line was replaced by its lumped capacitance at the point of fault. Figure 7, part a, gives a one-line diagram of the system studied; parts b and c, respectively, show the positive- and zero-sequence impedance diagrams for part a. Lowercase letters are used to differentiate the indicated impedances in figures 7 from the resultant effective impedances viewed from the fault which are represented by capitals.

In figure 7 the positive- and zero-sequence fundamental-frequency impedances viewed from the fault are

$$Z_1 = \frac{(r_1 + jx_1)x_{c1}}{x_{c1} - x_1 + jr_1} = R_1 + jX_1$$

$$Z_0 = \frac{[r_0 + 3r_n + j(x_0 + 3x_n)]x_{c0}}{x_{c0} - (x_0 + 3x_n) + j(r_0 + 3r_n)} = R_0 + jX_0$$

For a ground-fault neutralizer, $x_{c0} \cong x_0 + 3x_n$, and

$$R_0 \cong \frac{(x_0 + 3x_n)x_{c0}}{r_0 + 3r_n}$$

The coil is generally tuned so that X_0 has a very small positive value.

Resistance Neglected. With all resistance neglected in figure 7, transient voltages are expressed in appendix A in terms of the fundamental-frequency impedances viewed from the fault and the ratio of the positive to the zero-sequence capacitive reactance.

With resistance neglected, the fundamental-frequency impedances viewed from the fault in figure 7 are:

$$Z_1 = j\frac{x_1 x_{c1}}{x_{c1} - x_1} = 0 + jX_1$$

$$Z_0 = j\frac{(x_0 + 3x_n)x_{c0}}{x_{c0} - (x_0 + 3x_n)} = 0 + jX_0$$

With $(x_0 + 3x_n)$ greater than x_{c0}, X_0 is negative.

Figures 8 and 9 for line-to-ground and double-line-to-ground faults, respectively, give the maximum transient voltages in

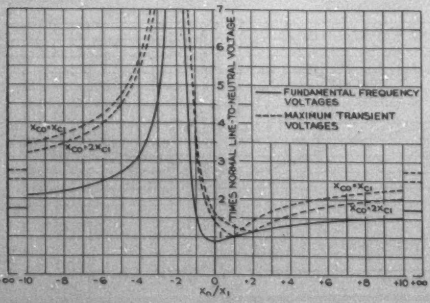


Figure 8. Transient voltages with resistance neglected for system shown in figure 7. Line-to-ground fault. Maximum voltage-to-ground of unfaulted phases at the fault

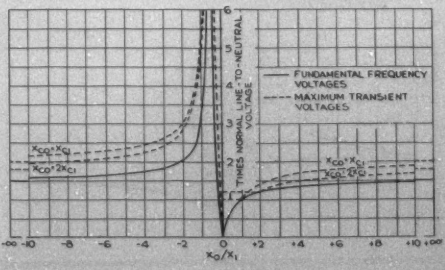


Figure 9. Transient voltages with resistance neglected for system shown in figure 7. Double-line-to-ground fault. Maximum voltage-to-ground of unfaulted phase at the fault

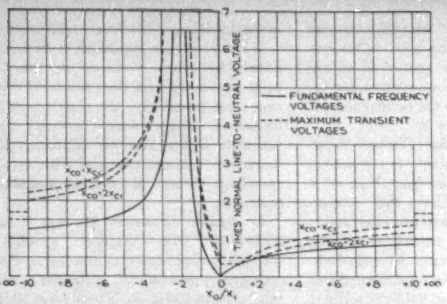


Figure 10. Transient voltages with resistance neglected for system shown in figure 7. Line-to-ground fault. Maximum zero-sequence voltage at the fault

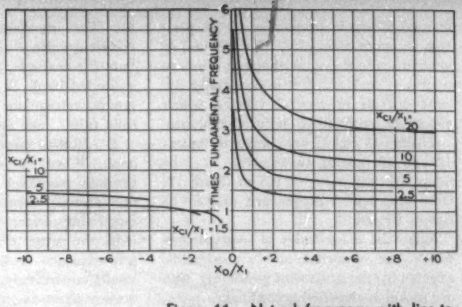


Figure 11. Natural frequency with line-to-ground fault for system shown in figure 7, with resistance neglected and $x_{c0} = x_{c1}$

per unit of normal peak line-to-neutral voltage on the unfaulted phases at the fault in terms of X_0/X_1 for the system shown in figure 7. The curves in figures 8 and 9 were calculated from equations 19 or 20 and 23, respectively, of appendix *A* with $\theta_0 = 90$ degrees. Since resistance is neglected there will be no decrement, and therefore the peak value of the fundamental-frequency term indicated in figures 8 and 9 by full-line curves, and the peak value of the natural-frequency term are added directly (since they must eventually come in phase) to give the total maximum voltage. Peak values of transient voltages are shown by dashed lines for $x_{c0} = x_{c1}$ and $x_{c0} = 2x_{c1}$.

Figure 10, for the same conditions as figure 8, gives the maximum transient zero-sequence voltage at the fault for a line-to-ground fault calculated from equation 18, appendix *A*. The maximum zero-sequence transient voltage at the fault for a double-line-to-ground fault will be one-third the voltage of the unfaulted phase given by figure 9. See equation 23, appendix *A*.

With X_0/X_1 between 0 and -2 in figure 8, and between 0 and -0.5 in figure 9, the natural frequency, ω_n, is less than unity. See equations 21 and 24, appendix *A*. Higher transient values than those plotted in this region could therefore have been obtained with $\theta_0 = 0$ degrees instead of 90 degrees.

The natural frequency, ω_n, in per unity of fundamental frequency given by (21) for the line-to-ground fault with $x_{c0} = x_{c1}$ is plotted in figure 11, with abscissa X_0/X_1 and parameter x_{c1}/x_1. From figure 11, at the resonant point ($X_0/X_1 = -2$), the natural frequency is unity and for values of X_0/X_1 between -2 and 0, less than unity. The region between 0 and -2 corresponds to a very low ratio of x_{c1}/x_1, such as would probably not be encountered in a practical system operating normally.

Method of Grounding

Reactance Grounding

Figures 8 and 9 can be used to determine transient voltages with resistance neglected when the neutral is solidly grounded or grounded through any reactance, including a ground-fault neutralizer. For a solidly grounded neutral, $x_n = 0$. For a ground-fault neutralizer with resistance neglected, $3x_n + x_0 = x_{c0}$, and $X_0 = \infty$.

Comparison of Resistance and Reactance Grounding

A comparison of the effects of resistance and reactance grounding on the fundamental-frequency fault voltages following a line-to-ground fault can be obtained from figures 1, 4, and 5 when the positive- and zero-sequence impedances viewed from the fault are known.

To compare the effects of reactance and resistance grounding on transient overvoltages following faults, the curves of figure 8 for a line-to-ground fault have been replotted in figure 12 in terms of the impedances indicated in figure 7. Figures 12 and 13 show the magnitudes of the transient voltages which may be obtained following a line-to-ground fault when the neutral is grounded through reactance and through resistance, respectively, with $x_0 = x_1$ and $x_{c0} = x_{c1}$.

The voltages in figure 13 and some points in figure 12 were determined by using a miniature system having the characteristics and features described in appendix *B*. The full-line curves correspond to fundamental-frequency voltages for different values of the ratio of $3x_n/x_1$ or $3r_n/x_1$, where x_n is the grounding reactance in the case of figure 12 and r_n is the grounding resistance in the case of figure 13. As will be noted, exceptionally high voltages are not obtained until the capacitive reactance x_{c0} becomes small compared with x_1. This condition corresponds to a system having a very large amount of line-charging capacity compared with the connected generation. Also, it will be noted that transient voltages do not exceed twice the fundamental-frequency voltages with either reactance or resistance grounding, for the conditions assumed.

The sustained voltages for resistance-grounded systems are generally higher than those for corresponding reactance-grounded systems. This is particularly true if the neutral grounding ohms are selected to give the same value of short-circuit current, as can be seen from an analysis of figures 12 and 13. For high ohmic values of neutral-grounding impedance, the transient voltages may be higher for reactance-grounded than for resistance-grounded systems. For low ohmic values, the natural-frequency component of voltage for resistance-grounded systems decreases and becomes negligible for values of $3r_n/x_1 < 5$. Accordingly, a reactance-grounded system may not subject the protective equipment to as high sustained voltages as a resistance-grounded system, but from the standpoint of natural-frequency overvoltages, particularly those associated with switching phenomena, the resistance-grounded neutral may be more desirable.[15,16]

Figures 14 and 15 show the corresponding neutral-to-ground voltages for the cases shown in figures 12 and 13, respectively. This information is of value in indicating the voltages which may occur from neutral-to-ground under the condition of line-to-ground faults. Exceptionally, high overvoltages are not obtained at the neutral except for systems which have a relatively large amount of

connected line in proportion to the positive-sequence reactance. The curves, in general, have the same shape as those in figures 12 and 13, as it is essentially the shift or rise in neutral voltage which causes the overvoltage on the open phases.

Figures 16 and 17 are similar to figures 12 and 13, except that $x_{c0}/x_{c1} = 2$ in figure 16, and $x_0/x_1 = 0.5$ in figure 17. Only transient voltages are plotted in figures 16 and 17.

Since the magnitudes of overvoltages which are obtained are considerably affected by the method of grounding, this discussion is classified accordingly.

1. *Solidly Grounded System.* There are many degrees of *solid grounding* and the term means very little as far as the overvoltages are concerned, as it depends upon the number, location, and kilovolt-ampere capacity of the grounding points. However, if the grounded-neutral system is considered to be one in which grounded-neutral lightning arresters may be used (line-to-ground sustained voltages not to exceed 140 per cent to 150 per cent of normal), it becomes apparent that the ratio of X_0/X_1 should be kept below about 3 or 4. See figures 1, 2, and 6. Accordingly, this will ordinarily mean that a large percentage of all transformers or machines must be solidly grounded.

Systems operating in this classification, that is, X_0/X_1 not greater than 3 or 4, have a maximum transient line-to-ground voltage on the unfaulted phases not exceeding 2.0 times normal (see figures 8 and 9). The maximum neutral-to-ground transient voltage at any point in the system, for example, the neutral of an ungrounded bank, is about normal line-to-ground voltage due to the occurrence of a solid fault. See figure 10.

2. *Neutral Grounded Through Reactance.* When a system is grounded through reactance less than that of a ground-fault neutralizer, the zero-sequence impedance viewed from the fault is inductive rather than capacitive and the zero-sequence resistance is relatively small; accordingly, the fundamental-frequency phase-to-ground voltages will not exceed normal line-to-line voltage, and the neutral-to-ground voltage will not exceed normal line-to-neutral voltage. See figures 1–6, with X_0/X_1 positive and $R_0/X_1 < X_0/X_1$.

Following a fault, systems with reactance grounds will have maximum transient voltages to ground on the unfaulted phases not exceeding 2.73 times normal. The voltage to ground of the neutral will not exceed 1.67 times normal line-to-neutral voltage. See figures 8–10.

3. *Neutral Grounded Through Resistance.* When a system is grounded through resistance, the zero-sequence impedance viewed from the fault may be inductive or capacitive, depending upon the number and location of the grounding points and the amount of connected line or cable. With low-resistance grounds, X_0 will ordinarily be positive and the fundamental-frequency phase-to-ground voltages will, in general, not exceed normal line-to-line voltage and the neutral-to-ground voltages will not exceed normal line-to-neutral voltage. With high-resistance grounds, X_0 may be negative. In that case, phase-to-ground voltages may be greater than normal line-to-line voltages, and neutral-to-ground voltages greater than normal line-to-neutral voltages. See figures 1, 3, 4, and 5.

If low-resistance grounding is used, the natural-frequency voltages are practically eliminated and the maximum voltages are essentially the fundamental-frequency voltages which, however, are generally higher than the fundamental-frequency voltages obtained with corresponding values of neutral-grounding reactance.

4. *System Grounded Through Fault Neutralizer.* For systems grounded through ground-fault neutralizers, with resistance neglected, X_0 is infinite; with resistance included, R_0 is very large while X_0 is negative. Based on either assumption, the fundamental-frequency voltages on the unfaulted phases at the fault following a line-to-ground fault are essentially line-to-line voltages. See figure 1. The maximum transient voltages-to-ground on the unfaulted phases are less than 2.73 times normal, and of the neutral-to-ground less than 1.67 times normal line-to-neutral voltage. See figures 8 and 10.

Higher voltages may be obtained at points removed from the ground-fault neutralizers where there is in effect concentrated an appreciable amount of zero-sequence capacitance to ground. This indicates the advisability of placing the ground-fault neutralizer at the centers of the system, and also the desirability of using, under certain conditions, more than one ground-fault neutralizer.

5. *Isolated Neutral.* In the case of an isolated-neutral system, X_0 is negative and of the order of magnitude of the capacitive reactance while R_0/X_1 is relatively small. From figures 1, 4, and

Figure 12. Transient and fundamental-frequency voltages with resistance neglected for system shown in figure 7. Line-to-ground fault. Maximum voltage-to-ground of unfaulted phases at the fault

$X_0 = X_1$ $X_{c0} = X_{c1}$

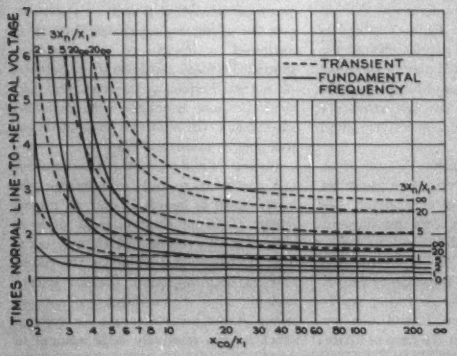
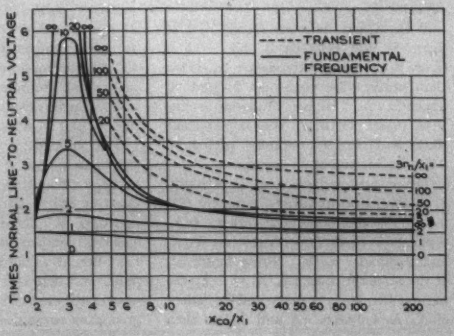


Figure 13. Transient and fundamental-frequency voltages for system shown in figure 7. Line-to-ground fault. Maximum voltage-to-ground of unfaulted phases at the fault

$X_0 = X_1$ $X_{c0} = X_{c1}$



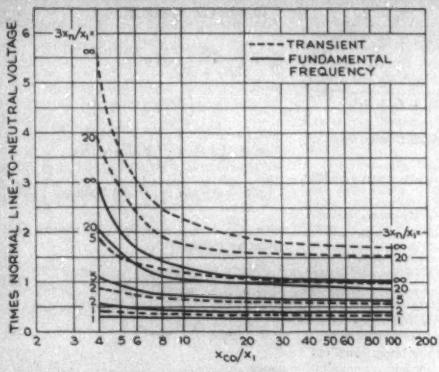


Figure 14. Transient and fundamental-frequency voltages with resistance neglected for system shown in figure 7. Line-to-ground fault. Maximum voltage-to-ground at the neutral

$x_0 = x_1$ $x_{c0} = x_{c1}$

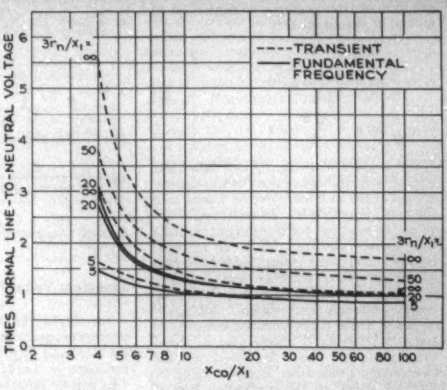


Figure 15. Transient and fundamental-frequency voltages for system shown in figure 7. Line-to-ground fault. Maximum voltage-to-ground at neutral

$x_0 = x_1$ $x_{c0} = x_{c1}$

5, the fundamental-frequency voltages obtained may be in excess of normal line-to-line voltage; and in some cases, particularly when the system is large in extent, considerably in excess, so that a very undesirable condition is created when faults occur. The fact that such voltages may be obtained makes it highly desirable that under no condition of operation shall a system lose its grounding points, if by so doing it is liable to be in the region of resonance. Otherwise, damage to the protective equipment or flashover of major equipment may result. The minimum voltage rating commonly used in isolated-neutral arresters is 1.83 times normal line-to-neutral voltage.

Voltages Distant From Fault

The fundamental-frequency and transient voltages given by the curves in this paper are at the point of fault. Under certain conditions higher voltages than those occurring at the point of fault may be obtained. This is particularly true at points which are located at a distance from the fault and the grounding points, but located where there is, in effect, an appreciable amount of zero-sequence capacitance to ground. The fundamental zero-sequence voltage at such points can be readily calculated from the zero-sequence voltage at the fault and the zero-sequence network. Figure 18 shows the simplified zero-sequence impedance diagram with the identity retained of the fault point F and point P, at which voltage is required. The zero-sequence voltage at P is

$$V_{a0}\ (\text{at } P) = V_{a0}\ (\text{at } F)\ \frac{Z_z}{Z_y + Z_z}$$

With Z_z capacitive reactance and Z_y inductive reactance, the zero-sequence voltage at P will be higher at P than at F. If it is appreciably higher, additional calculations are required for determining both fundamental- and natural-frequency voltages. The case of higher fundamental-frequency voltages at points distant from the fault than at the point of fault has been discussed in a recent paper.[9]

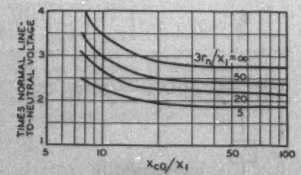


Figure 16. Maximum transient unfaulted-phase voltage-to-ground for system shown in figure 7. Line-to-ground fault. Neutral grounded through resistance

$x_0 = x_1$ $x_{c0} = 0.5x_{c1}$

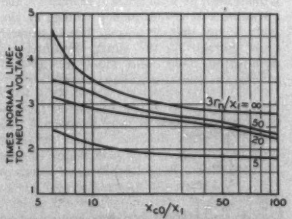


Figure 17. Maximum transient unfaulted-phase voltage-to-ground for system shown in figure 7. Line-to-ground fault. Neutral grounded through resistance

$x_0 = 0.5x_1$ $x_{c0} = x_{c1}$

Nomenclature

$Z_1 = R_1 + jX_1$, $Z_0 = R_0 + jX_0$ = positive and zero-sequence fundamental-frequency impedances, respectively, viewed from the fault point

R_f = fault resistance

$Z_1(p)$, $Z_0(p)$ = operational expressions for the positive and zero-sequence impedances, respectively, viewed from the fault point

Lower case letters apply to the circuit shown in figure 7.

$z_1 = r_1 + jx_1$, $z_0 = r_0 + jx_0$ = positive and zero-sequence fundamental-frequency impedances, respectively, from neutral to the fault point

$z_n = r_n + jx_n$ = fundamental-frequency impedance between neutral and ground

x_{c1}, x_{c0} = positive and zero-sequence fundamental-frequency capacitive reactances, respectively, of transmission line

$\theta = \theta_0 + t$ = angle between direct axis of reference machine and axis of phase a

ω_n = natural frequency in times fundamental frequency

Appendix A. Fundamental- and Natural-Frequency Voltages

The instantaneous phase voltages at any point in a balanced three-phase system in

per unit of crest voltages to neutral or to ground at that point are

$$\left.\begin{aligned} e_a &= -\sin\theta \\ e_b &= \frac{1}{2}\sin\theta + \frac{\sqrt{3}}{2}\cos\theta \\ e_c &= \frac{1}{2}\sin\theta - \frac{\sqrt{3}}{2}\cos\theta \end{aligned}\right\} \quad (1)$$

Let e and i with appropriate subscripts refer to instantaneous values of voltages-to-ground at the fault and currents flowing into the fault, respectively. In reference 17 are given the relations for transformation from three-phase quantities (a, b, c) to symmetrical-component quantities for the case of instantaneous currents and voltages, including the transient as well as the fundamental-frequency components. An application of these transformation relations is given in reference 5, except that α and β components are used. However, for the case under consideration, $Z_\alpha(p) = Z_\beta(p) = Z_1(p) = Z_2(p)$, so the application here is quite similar. Using the generalized method of symmetrical components, the following equations are obtained.

Line-to-Ground Fault (Phase a)

$$i_{a1} = i_{a2} = i_{a0} = \frac{-\sin\theta}{2Z_1(p) + Z_0(p) + 3R_f}$$

$$e_{a0} = -i_{a0}Z_0(p) = \frac{Z_0(p)\sin\theta}{2Z_1(p) + Z_0(p) + 3R_f} \quad (2)$$

$$e_b = \frac{1}{2}\sin\theta + \frac{\sqrt{3}}{2}\cos\theta + \frac{Z_0(p) - Z_1(p)}{2Z_1(p) + Z_0(p) + 3R_f}\sin\theta \quad (3)$$

$$e_c = \frac{1}{2}\sin\theta - \frac{\sqrt{3}}{2}\cos\theta + \frac{Z_0(p) - Z_1(p)}{2Z_1(p) + Z_0(p) + 3R_f}\sin\theta \quad (4)$$

Double Line-to-Ground Fault (Phases b and c)

$$i_{a0} = -(i_{a1} + i_{a2}) = \frac{\sin\theta}{Z_1(p) + 2Z_0(p) + 6R_f}$$

$$e_{a0} = -i_0Z_0(p) = \frac{-Z_0(p)\sin\theta}{Z_1(p) + 2Z_0(p) + 6R_f} \quad (5)$$

$$e_a = -\frac{3Z_0(p) + 6R_f}{Z_1(p) + 2Z_0(p) + 6R_f}\sin\theta \quad (6)$$

Line-to-Line Fault (Phases b and c)

$$e_a = -\sin\theta \quad (7)$$

$$e_b = e_c = \frac{1}{2}\sin\theta \quad (8)$$

Fundamental-Frequency Components of Voltage

Introducing vector quantities[4] by replacing $-\sin\theta$ by unity, $\cos\theta$ by $-j$, and $Z_1(p)$ and $Z_0(p)$ by Z_1 and Z_0, respectively, in (2)–(6), crest voltages of fundamental-frequency are obtained.

Line-to-Ground Fault (Phase a)

$$e_{a0} = -\frac{Z_0}{2Z_1 + Z_0 + 3R_f} \quad (9)$$

$$e_b = -\frac{1}{2} - j\frac{\sqrt{3}}{2} - \frac{Z_0 - Z_1}{2Z_1 + Z_0 + 3R_f} \quad (10)$$

$$e_c = -\frac{1}{2} + j\frac{\sqrt{3}}{2} - \frac{Z_0 - Z_1}{2Z_1 + Z_0 + 3R_f} \quad (11)$$

Double Line-to-Ground Fault (Phases b and c)

$$e_{a0} = \frac{Z_0}{Z_1 + 2Z_0 + 6R_f} \quad (12)$$

$$e_a = \frac{3Z_0 + 6R_f}{Z_1 + 2Z_0 + 6R_f} \quad (13)$$

Transient Voltages

To obtain the natural-frequency components of equations 2–6 necessitates replacing $Z_1(p)$ and $Z_0(p)$ by their operational expressions in terms of system constants. This can be done only when the system is given. For the system represented in figure 7,

$$Z_1(p) = \frac{(r_1 + px_1)\dfrac{x_{c1}}{p}}{r_1 + px_1 + \dfrac{x_{c1}}{p}} \quad (14)$$

$$Z_0(p) = \frac{[r_0 + 3r_n + p(x_0 + 3x_n)]\dfrac{x_{c0}}{p}}{r_0 + 3r_n + p(x_0 + 3x_n) + \dfrac{x_{c0}}{p}} \quad (15)$$

Resistance Neglected. With resistance neglected in figure 7, $Z_1(p)$, $Z_0(p)$, Z_1, and Z_0 become,

$$Z_1(p) = \frac{px_1x_{c1}}{p^2x_1 + x_{c1}} \quad (14a)$$

$$Z_0(p) = \frac{p(x_0 + 3x_n)x_{c0}}{p^2(x_0 + 3x_n) + x_{c0}} \quad (15a)$$

$$Z_1 = \frac{jx_1x_{c1}}{x_{c1} - x_1} = jX_1 \quad (16)$$

$$Z_0 = j\frac{(x_0 + 3x_n)x_{c0}}{x_{c0} - (x_0 + 3x_n)} = jX_0 \quad (17)$$

Line-to-Ground Fault. With a line-to-ground fault at F on phase a in figure 7, the instantaneous zero-sequence voltage at the fault in per unit of normal line-to-neutral peak voltage at the fault, obtained by substituting (14a) and (15a) in (2) and solving the operational equations is

$$e_0 = \frac{Z_0}{2Z_1 + Z_0}\sin\theta - \frac{2\left(\dfrac{x_0 + 3x_n}{x_{c0}} - \dfrac{x_1}{x_{c1}}\right)}{\left(\dfrac{2}{x_{c0}} + \dfrac{1}{x_{c1}}\right)\left[2x_1 + x_0 + 3x_n - x_1(x_0 + 3x_n)\left(\dfrac{2}{x_{c0}} + \dfrac{1}{x_{c1}}\right)\right]} \times \left(\sin\theta_0\cos\omega_n t + \frac{1}{\omega_n}\cos\theta_0\sin\omega_n t\right)$$

In terms of X_0 and X_1,

$$e_{a0} = \frac{X_0}{2X_1 + X_0}\sin\theta - \frac{2\left(\dfrac{x_{c1}}{x_{c0}}X_0 - X_1\right)}{\left(1 + 2\dfrac{x_{c1}}{x_{c0}}\right)(2X_1 + X_0)} \times \left(\sin\theta_0\cos\omega_n t + \frac{1}{\omega_n}\cos\theta_0\sin\omega_n t\right) \quad (18)$$

with $x_{c0} = x_{c1}$, equation 18 checks that given by Fallou.[10]

$$e_b = \frac{3}{2}e_0 + \frac{\sqrt{3}}{2}\cos\theta \quad (19)$$

$$e_c = \frac{3}{2}e_0 - \frac{\sqrt{3}}{2}\cos\theta \quad (20)$$

where

$$\omega_n = \sqrt{\frac{2x_1 + x_0 + 3x_n}{2x_1(x_0 + 3x_n)\left(\dfrac{1}{x_{c0}} + \dfrac{1}{2x_{c1}}\right)}} = \sqrt{\frac{\dfrac{X_0}{X_1}\left(\dfrac{x_{c1}}{x_1} + 2\dfrac{x_{c1}}{x_{c0}}\right) + 2\left(\dfrac{x_{c1}}{x_1} - 1\right)}{\dfrac{X_0}{X_1}\left(2\dfrac{x_{c1}}{x_{c0}} + 1\right)}} \quad (21)$$

Double-Line-to-Ground Fault. With a double-line-to-ground fault at F on phases b and c, the instantaneous zero-sequence and phase a voltage-to-ground at the fault in per unit of normal line-to-neutral peak voltage at the fault are obtained by substituting (14a) and (15a) in (5) and (6) and solving the operational equations. Expressed in terms of the positive- and zero-sequence reactances viewed from the fault,

$$e_0 = -\frac{X_0}{X_1 + 2X_0}\sin\theta + \frac{\dfrac{x_{c1}}{x_{c0}}X_0 - X_1}{\left(2 + \dfrac{x_{c1}}{x_{c0}}\right)(X_1 + 2X_0)} \times \left(\sin\theta_0\cos\omega_n t + \frac{\cos\theta}{\omega_n}\sin\omega_n t\right) \quad (22)$$

$$e_a = 3e_0 \quad (23)$$

where

$$\omega_n = \sqrt{\frac{x_1 + 2(x_0 + 3x_n)}{2x_1(x_0 + 3x_n)\left(\dfrac{1}{2x_{c0}} + \dfrac{1}{x_{c1}}\right)}} \quad (24)$$

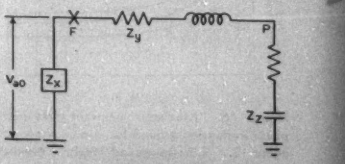


Figure 18. Simplified zero-sequence impedance diagram

Appendix B. Description of Miniature System

The miniature equivalent system used in making the laboratory tests is shown in figure 19.

The reactors used in this system had low ratios of resistance to reactance which varied from about 0.01 to 0.04 at 60 cycles depending upon the portion of the total winding being used. The miniature power

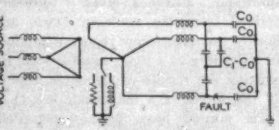


Figure 19. Miniature equivalent system

transformer was also of low-loss design so that the entire system caused relatively low damping of natural-frequency oscillations. This was desirable for purposes of checking calculations based on no-loss circuits.

The miniature system was energized from a three-phase 110-volt 60-cycle voltage source of such capacity that its terminal voltage remained essentially constant regardless of transient conditions imposed by faults in the equivalent circuits.

A synchronous commutator was used to apply and remove repeatedly the fault in synchronism with the system voltage. The commutator drum was driven by an 1,800-rpm synchronous motor by means of a ten-to-one gear reduction so that one revolution of the drum was completed every 20 cycles. The contacts on the switch were so made that during these 20 cycles the fault would be on 5 cycles and off 15 cycles. The relatively long period during which the fault was off afforded ample time for steady-state conditions to be reached before the switching operation was repeated.

A cathode-ray oscilloscope was used to measure the transient voltages. Another contactor on the synchronous commutator was used to control the grid on the cathode-ray tube so that the light beam would appear on the screen for only one cycle out of each 20. This made it possible to obtain a clear picture of the transient voltages during the period of particular interest.

The contactors on the commutator were mounted on a rack which could be rotated to vary the instant of application of the fault corresponding to various points on the voltage wave. Thus it was possible to determine the maximum voltage that could be reached by selecting the angle of fault application which gave the highest transient voltage on the oscilloscope.

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Discussion

P. A. Jeanne: See discussion, page 395.

R. D. Evans, A. C. Monteith, and R. L. Witzke (all of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Concerning the results in the Clarke-Crary-Peterson paper, it may be observed that the simple form of network illustrated in figure 19 for transient analysis, might lead to appreciable error. The use of such a simple equivalent circuit reduces to an extent the usefulness of the results.

Also, in connection with this paper, the authors have carried the curves to negative value of X_0/X_1 whereas in the previous published work by Evans and Wright[1] only values for positive ratios were considered. The curves in the negative zone are no doubt correct from an academic point of view. However, we are inclined to question their practical use when high values of overvoltage are considered as the constants of the circuit will change in a direction tending to limit the magnitude of voltage. Such changes in circuit constants may be due to corona, magnetizing current of transformers, etc. The practical range of the curves is probably from -1 ratio to the positive values.

A value of X_0/X_1 of 3 to 4 is suggested for a safe application of a grounded-neutral lightning arrester. It is believed that in drawing this conclusion the effects of fault resistance have been ignored. When high values of fault resistance are considered the ratio of X_0/X_1 must be lowered if the fault is at the point of application of the arrester. In the work published by Monteith and Roman[2] it was considered improbable to have a fault at the point of application of the arrester since the arrester should prevent flashover. When the fault is considered at a point other than where the arrester is applied, the ratio of 3 to 4 for X_0/X_1, can be selected and the criterion will be entirely independent of fault resistance.

(See also discussion, page 412.)

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1. Some Effects of Unbalanced Faults, R. D. Evans and S. H. Wright. Electrical Engineering, June 1931, pages 415–20.

2. Application of Station-Type Lightning Arresters, A. C. Monteith and W. G. Roman. *Electric Journal*, March 1938, pages 93–8.

Edith Clarke, S. B. Crary, and H. A. Peterson: In answer to the discussion by Messrs. Evans, Monteith, and Witzke:

The simple network of figure 19, although an approximation, gives transient voltages at the point of fault not *less* than the maximum transient voltages which may occur (see "Basis of Study," 9), and thus enables us to draw conclusions in regard to the maximum transient voltages which can occur at the point of fault for various conditions of grounding.

The curves for negative values of X_0/X_1 have been found practical in determining voltages corresponding to high negative values of X_0/X_1 beyond the resonance region. As pointed out in the paper, the very high voltages indicated by the curves would not be obtained in the resonance region, since they are critical values and therefore greatly influenced by saturation, corona, and variation of machine reactances with time (see "Basis of Study," 5 and 6). They are useful, however, in that they indicate regions where high voltages will be obtained, that is, voltages in excess of normal line-to-line voltages.

The effect of fault resistance was not ignored in suggesting a value of X_0/X_1 between 3 and 4 for safe application of a grounded-neutral arrester. This conclusion is based on the curves of figure 6, which include the effect of fault resistance. The curves apply to cases in which the arrester and fault locations are far enough from each other so that mutual ground resistance of the arrester and fault is not encountered, and yet not so remote from each other that voltages to ground at the arrester are appreciably different from those indicated. Figure 6 in the region of $X_0/X_1 = 1$ to 5 checks the curves of figure 4 given by Messrs. Monteith and Roman in reference 8.

Power-System Transients Caused by Switching and Faults

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Synopsis: This paper summarizes the results of an investigation of transient voltages on power systems caused by switching and faults. The transient voltages on power systems as measured by the "klydonograph" are reviewed and compared with the flashover values of transmission-line insulation. It is shown that the higher values of transient voltages are produced by intermittent arcs. In part I, the various theories for the production of transient voltages of high magnitude as a result of intermittent arcs are reviewed and extended in order to obtain the highest voltages on typical polyphase systems with the range of natural frequencies and attenuation factors that are encountered in practice. Previous studies are of limited scope and apply principally to the case of an arcing ground on an ungrounded system. The present study shows broadly the range of transient voltages which may be produced with intermittent arcs and applies to switching operations as well as arcing grounds. A typical transmission system is studied with the aid of the a-c network calculator. One of the principal variable factors in this study is the method of system grounding and this includes a range of both resistance and reactance between the limits of a solidly grounded system and an ungrounded system. The study is carried out for four different conditions, namely: (1) arcing grounds, (2) de-energizing an unfaulted line section, (3) de-energizing a line section with a fault on one phase, and (4) de-energizing a line section with a fault on two phases. The results of this study are presented in graphical form in part II and show many interesting properties of systems with respect to the method of grounding, and the characteristics of transient voltages for the different switching and fault conditions. It is the authors' opinion that the transient voltages due to faults and switching deserve more attention than they have received within the last few years.

THE EXISTENCE of transient overvoltages on transmission (and distribution) systems as a result of circuit changes caused by switching operations or faults has long been recognized. Many years ago when transmission systems were first expanding, the effect of arcing grounds received a great deal of attention. The phenomena, however, were not thoroughly investigated at the time because suitable measuring and recording devices were not available and because the immediate difficulties were largely overcome by the adoption of the practice of grounding transmission systems. The invention by J. F. Peters[1] of the "klydonograph," the first really practical surge recorder, made possible the collection of a mass of field data on overvoltages. The introduction of this instrument stimulated extensive investigations of voltages caused both by lightning and other transients. In recent years, considerable attention has been directed to the lightning phase of the problem but other phases have largely been neglected. It is the authors' view that the time has come when further attention should be given to the problems of overvoltages caused by faults and switching operations. To them it seems quite possible that some of the multiphase faults on systems which are now attributed wholly to lightning may, in reality, be caused in part by voltages produced by intermittent arcs.

It is pertinent to review the operating experience which has been obtained on transmission lines in regard to overvoltages produced by switching surges arising from circuit changes or isolation of faulted conductors. Quite a number of klydonograph investigations have been reported in the literature and many of these segregate the overvoltages resulting from switching operations from those due to lightning. Extensive investigations were reported by Cox, McAuley, and Huggins;[2] Gross and Cox;[3] Lewis and Foust;[4] and by a number of European investigators. The Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell Telephone System, has also carried on some investigations and has made an excellent summary[5] of the more important published data.

The principal results of the switching surge studies made with the aid of the klydonograph have been summarized in figure 1. In this figure, curves *A* and *B* obtained from the original investigation by Cox, McAuley, and Huggins,[2] give the voltages due to energizing or de-energizing operations and the voltages due to faults with subsequent switching, respectively. Curve *C* gives a summary derived from the work of Lewis and Foust,[4] the most recent report of its kind. In order to give a more suitable scale for plotting the results of the surge studies all the surges of a magnitude less than twice normal have been disregarded. The Lewis and Foust paper, however, shows that of all the reported surges above normal voltage, 45 per cent were above twice normal. Figure 1 shows that the limiting value of the surges is about six times normal crest voltage, 5 per cent exceed five times normal, and 20 per cent exceed four times normal.

It will be noted from figure 1 that there is an upper limit to the voltage recorded, indicating the possibility of some limiting factor. Figure 2 shows the ratio of the voltage required to produce flashover, to the normal crest voltage, for different voltage transmission lines equipped with

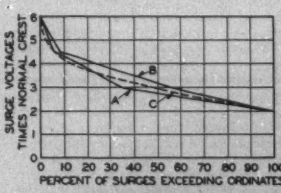

Figure 1. Distribution of surge voltages caused by switching and faults

A—Switching surges—Cox, McAuley, and Huggins

B—Surges from faults—Cox, McAuley, and Huggins

C—Switching surges—Lewis and Foust

A and *B*—Eighteen systems—1925 to 1926

C—Fourteen systems—1926 to 1930

the range of insulator units encountered in practice. The shape of the curve of figure 1 compared with the data given in figure 2, indicates that the magnitude of switching surges recorded could be limited by line flashover. While it is undoubtedly true that a considerable percentage of these switching operations take place with relatively little energy in the oscilla-

Paper number 39-48, recommended by the AIEE committees on power transmission and distribution, and protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 14, 1938; made available for preprinting December 27, 1938.

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The authors wish to acknowledge the assistance which they have received from their associates, particularly I. F. Krughoff, who carried out the principal part of the studies with the a-c network calculator.

1. For all numbered references, see list at end of paper.

tion and at relatively high frequency, it is also true that as systems expand the natural frequency of systems for switching operations decreases and the amount of energy in these oscillations increases. Thus, these factors tend to increase the importance of switching surges.

Part I. Mechanism of Producing Transient Overvoltages as a Result of Circuit Changes

The mechanism of producing transient overvoltages on transmission (and distribution) systems as a result of circuit changes caused by switching operations and faults will now be considered. The magnitude of these transient voltages, as shown in figure 1, will, under some conditions, exceed the sum of two components, (1) the final steady-state voltage, and (2) a transient voltage equal to the difference between it and the initial steady-state voltage. The value of this transient voltage has been assumed to be the one indicated by the conventional theory of circuit changes involving a single switching operation producing a simple circuit change such as a "make" or a "break." Thus the transient voltage, which is due to a "make" such as the sudden and permanent fault to ground, or a "break" such

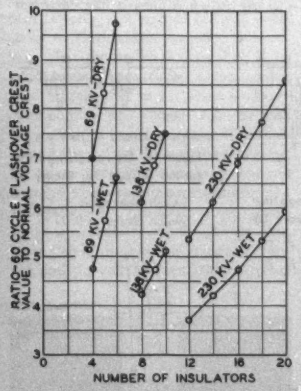


Figure 2. Sixty-cycle flashover voltage ratios for ten-inch suspension units

as the sudden and permanent de-energizing of a circuit, are relatively low in comparison with the maximum transient voltages that are known to have been produced by switching operations or faults. In a "simple circuit change" as the expression is used in this paper, it is assumed that the change caused by a fault or switching operation takes place through a path that changes abruptly from a perfectly conducting to a nonconducting condition, or vice versa.

It is known that the circuit changes which produce the higher values of transient voltages involve arc paths. It has also been recognized that the characteristics of the arc path have a relation to the overvoltages, but the nature of the phenomenon has, in general, not been well understood. A little consideration will show that the conditions for producing high transient overvoltages from switching or faults have in common these features of (1) a circuit change through a path involving an arc, and (2) a circuit change which differs from that of a single "make" or "break" as previously discussed.

In considering the characteristics of an arc path in respect to the production of transient overvoltages, two classes of factors may be recognized, namely:

1. Abrupt forcing of current zero and high extinction voltage.
2. Cumulative action from intermittent arcing.

The phenomenon involving the first of these, the abrupt forcing of current zero, is well known in the simple form by which high voltages are produced when inductive circuits are quickly opened. This is not likely to be encountered with conventional types of interrupting equipment for faults and switching operations on power transmission systems. Instead, the probable conditions for the production of overvoltages from the first factor include the opening of the magnetizing circuits of transformers, switching of induction regulators, and other similar operations.

The extinction voltage or the voltage across an arc just prior to its interruption is also a factor affecting the magnitude of transient overvoltages. This factor is of importance on low-voltage but not on high-voltage circuits. In general, it is the authors' opinion, as pointed out elsewhere,[6] that the factors of abrupt forcing of current zero and high extinction voltage are not responsible for producing the more important transient overvoltages on transmission systems. Accordingly, only the effect of cumulative action from intermittent arcing has been considered in this investigation.

Theories of Intermittent Arcing

Various theories of intermittent arcing have been proposed to account for the high voltages produced by arcing grounds on ungrounded systems. These theories were reviewed some 15 years ago by Peters and Slepian[7] and their designations for the principal ones as theory I, theory II, and theory III, have been retained. The application of these theories has been

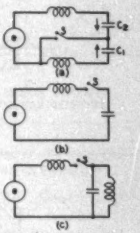


Figure 3. Simple circuits illustrating arcing grounds (a) and switching surges (b, c)

extended in this investigation to the full range of grounding conditions for the arcing ground case and to other cases involving switching and faults. These theories have been studied for simple and complicated circuits and it has been found that the basic features of theories I, II, and III are applicable but that to produce the highest voltages some modifications were necessary to cover the range of natural frequencies and attenuation factors, and the complication of circuits encountered on actual three-phase systems.

The close relationship between the intermittent arcing theories for arcing ground and switching cases makes it desirable to consider them together. The various theories of intermittent arcing are based on different assumptions in regard to the points at which the arc is interrupted and established or re-established. Thus the interruption of the arc may take place at a current zero close to a fundamental current zero or close to a natural- or high-frequency current zero. The arc may be established or re-established at a fundamental-frequency voltage crest or at a natural-frequency voltage crest.

In explaining these theories it is convenient to represent the intermittent arc by a switch, the opening and closing of which are controlled in accordance with the different theories. In using the switch to simulate an intermittent arc, certain dielectric characteristics of the arc path are assumed as discussed subsequently.

The essential features of the three theories are illustrated with the aid of the simplified circuits in figure 3. Figure 3a is a circuit for the representation of an arcing ground taking place at point *S*.

Figure 3b is a circuit used to represent the switching of a capacitor when supplied from a source through an inductance and corresponds to a switching operation where the disconnected section is left without a discharge path. Figure 3c is

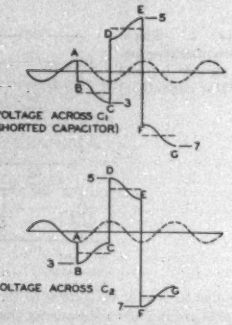


Figure 4a. Arcing ground (circuit 3a, theory III)

Switch closed at *A, C, E, G*
Switch opened at *B, D, F*

similar to the previous circuit but differs in that the disconnected section is provided with a discharge path.

The distinguishing features of the three theories of intermittent arcing may be obtained most readily by reference to table I. Part *a* of this table applies to the case of energizing a circuit, such as initiating an arcing ground in the circuit of figure 3a or the closing of a line section in the circuits of figures 3b and 3c. In all three theories the first closing of the switch is assumed to take place at the crest of the fundamental-frequency voltage across the switch, as this gives the highest transient voltages. In theories I and III the switch is always opened at the first current zero which is determined primarily by the natural- or high-frequency component of the current. In theory II the switch is not opened until the first fundamental current zero. In theory I the arc is assumed to restrike at the crest of the high-frequency oscillation across the switch. This restrike is simulated by reclosing the switch *S*. In theories II and III, the restrike takes place at the crest of the fundamental component of voltage across the switch.

In the second part of table I, the switching sequences are illustrated for the case of de-energizing a circuit. In this case the switch *S* is initially closed, and is opened at a fundamental current zero. After the first opening the restrikes and arc extinctions follow the same sequence as for energizing a circuit.

In order to clarify the above theories several cases of intermittent arcing are discussed in detail for the circuits of figure 3. First, the case of de-energizing the capacitor in the circuit of figure 3b is analyzed in accordance with theory III. The successive steps of building up the capacitor voltage are shown in figure 4b. Normal capacitor voltage has been added as a dotted curve. The capacitor voltage is normal and at point *A* the switch is opened and a charge is left on the capacitor. The switch voltage is now the algebraic sum of the generated voltage and the voltage due to the charge on the capacitor. It will reach a maximum of twice normal generated voltage crest at one-half cycle of fundamental frequency after the switch is opened. At the point *B* the capacitor voltage has a value of +1 in per unit values, whereas the normal capacitor voltage, with the switch closed, is −1. Now if the switch is closed at this time the capacitor voltage will be accelerated toward a value of −1 but because of the circuit inductance or inertia the voltage will overshoot and, without damping, will reach a value of −3. If now the switch is opened, the capacitor will have a charge corresponding to a voltage of −3. If the switch is again reclosed one-half cycle after opening, the voltage will be accelerated from −3 toward a value of +1 but will overshoot to a

Table I. Comparison of Theories of Intermittent Arcing

(a) Initial Condition—Circuit Open

Theory	First Close*	First Open**	First Restrike*	Second Open**	Second Restrike*
I	FF	NF	NF	NF	NF
II	FF	FF	FF	FF	FF
III	FF	NF	FF	NF	FF

(b) Initial Condition—Circuit Closed

Theory	First Open**	First Restrike*	Second Open**	Second Restrike*	Third Open**
I	FF	NF	NF	NF	NF
II	FF	FF	FF	FF	FF
III	FF	FF	NF	FF	NF

* Closing occurs at a voltage crest of FF or NF component.

** Opening occurs at a current zero, determined principally by the FF or NF component.

FF = Fundamental frequency.

NF = Natural or high frequency.

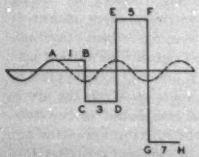


Figure 4b. De-energizing a line section (circuit 3b, theory III)

Switch opened at *A, C, E, G*
Switch closed at *B, D, F, H*

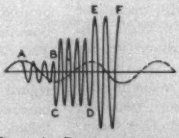
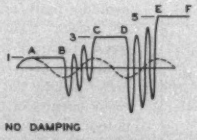


Figure 4c. De-energizing a line section (circuit 3c, theory III)

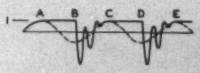
Switch opened at *A, C, E*
Switch closed at *B, D, F*



NO DAMPING

Figure 4d. De-energizing a line ?ion (circuit 3b, theory II)

Switch opened at *A, C, E*
Switch closed at *B, D, F*



WITH DAMPING − LIMIT = 3

Figure 4e. De-energizing a line section (circuit 3b, theory II)

Switch opened at *A, C, E*
Switch closed at *B, D*

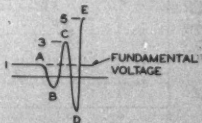


Figure 4f. De-energizing a line section (circuit 3b, theory I)

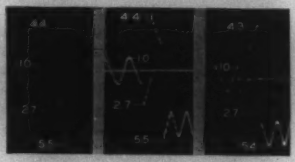
Switch opened at *A, C, E*
Switch closed at *B, D*

value of +5. It can be seen that the voltage builds up according to the series, 1, 3, 5, 7, . . . and will have no limit if damping is neglected. In this analysis it has been assumed that the inductance is small and that the natural frequency of the circuit is very high in comparison to the fundamental frequency.

Theory III has also been illustrated in figure 4*c* for the circuit of figure 3*c*. This case differs from that of figure 4*b* only in that the capacitor voltage oscillates around zero during the time the switch is open. The capacitor voltage is assumed to be the same in both cases at the time the switch is reclosed. The curves are derived on the assumption of no damping in the circuit.

In figure 4*a* are shown the voltages across the capacitors C_1 and C_2 of the circuit shown in figure 3*a*. In this case an arcing ground is simulated by opening and closing the switch S in accordance with theory III. The capacitors are assumed to be of equal capacitance and the circuit inductance is very low, so that one-half the generated voltage appears across each capacitor with the switch open. If the switch is closed at A, the voltage across capacitor C_1 oscillates around zero because the generated voltage is not impressed on this mesh. With C_1 short-circuited, the steady-state voltage across C_2 is twice normal. Therefore, when the switch S is closed, capacitor C_2 is accelerated toward twice normal but will overshoot to three times normal. Now assume that the switch is opened at B, at which time C_1 has a charge corresponding to a voltage −1 and C_2 has a charge corresponding to a voltage −3. Because these charges are in opposite directions around the circuit through the generator, the capacitors will not discharge but will equalize with a charge corresponding to a voltage of −2. The steady-state voltage across the capacitor will then be the algebraic sum of one-half the generated voltage, and the voltage due to the charge on the capacitor. By referring to figure 4*a* it can be seen that the voltage across both capacitors is equal to these steady-state values at the instant the switch is opened and as the initial and steady-state voltages are equal, there will be no transient.

If the switch is reclosed at C the voltage across capacitor C_1 will again oscillate around zero. With C_1 short-circuited the steady-state voltage across C_2 is twice normal. Therefore, when the switch is closed, the voltage of C_2 is accelerated from −1 toward twice normal but will overshoot to +5 times normal. Now assume that the switch is again opened at D, at which time C_1 has a charge corresponding to a voltage of +3 and C_2 has a charge corresponding to a voltage of +5. These charges will equalize leaving a charge corresponding to a voltage of +4 on each capacitor. Adding normal capacitor voltages to the voltage due to residual charges gives a voltage of +3 across C_1 and of +5 across C_2. These are steady-state voltages, and as they are the same as the corresponding voltages, at the instant the switch is opened, there will be no transient. It should be noted that the capacitor voltages build up according to the series 1, 3, 5, . . . which is the same as for the switching operation in figure 4*b*. Thus it can be seen that arcing grounds and switching operations may build up high voltages by the same mechanism of intermittent arcing.



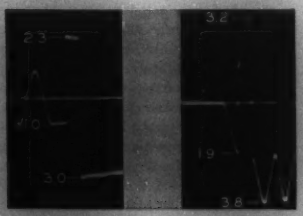
(*a*) (*b*) (*c*)

Figure 6. Arcing ground (circuit 3a, theory III)

(*a*)—Voltage across capacitor C_1

(*b*)—Voltage across capacitor C_2

(*c*)—Switch voltage



(*a*)—Capacitor voltage (*b*)—Switch voltage

Figure 5. De-energizing a line section (circuit 3b, theory III)

In figure 4*d* theory II is illustrated for the circuit of figure 3*b*. This differs from figure 4*b* in that the switch is not opened at the first current zero which is controlled by the natural-frequency component, but it is opened at a later instant corresponding to the fundamental current zero. Theory I is illustrated in figure 4*f* for the circuit of figure 3*c*. In this case the point of switching is controlled entirely by the high frequency. It is assumed that the oscillation is of very high frequency and the fundamental does not change during the interval of time considered.

In the above cases no damping was considered. Damping may appreciably affect the shape of the curves and will definitely limit the maximum voltages obtainable.[8] The effect of damping can be seen by comparing figures 4*d* and 4*e*. In figure 4*e* the high-frequency component of the capacitor voltage is assumed to be damped out in one-half cycle of the fundamental. The voltage is limited to three times normal under the assumed conditions of damping. In practical circuits the damping usually will not be as large as considered in figure 4*e* but will be large enough to require consideration.

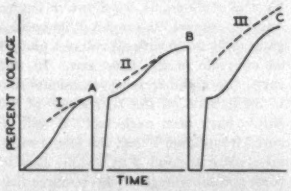


Figure 7. Dielectric recovery characteristics assumed for conditions of figure 5b

Note: Corresponds to the abstract circuit of figure 3*b*. All physical circuits have capacitances on source side which will introduce additional oscillations such as shown in figure 5*b*. Such demand different dielectric recovery characteristics to obtain the two restrikes shown

Another factor which cannot be neglected is the ratio of the natural frequency to the frequency of the generated voltage. In the above cases this ratio has been assumed to be very high. If this ratio is low the voltage will not build up as shown; the mechanism will be the same but the magnitudes will be less. For example, if in figure 4*b* the ratio were low the voltage would not build up to three times normal with one restrike because the fundamental decreases appreciably by the time the high-frequency component reaches its negative crest value. In many actual systems the natural frequency of the circuit may not be much above the supply frequency. For example, in a Petersen-coil grounded system the principal natural frequency is the same as the fundamental frequency.

At this point it is desirable to present some oscillograms of circuit transients in accordance with the foregoing discussion. While these oscillograms were actually taken on the a-c network calculator used

in the general studies discussed subsequently, it is sufficient for present purposes to consider them as transients obtained on simplified circuits of figure 3 subjected to switching transients in accordance with theories I, II, and III. Typical oscillograms are shown in figures 5 and 6. Figure 7 is a replot of the oscillogram of figure 5*b* with all voltages plotted on one side of the time axis. In this curve the high-frequency transients due to oscillations on the source side of the switch have been neglected. It will be noted from figure 7 that the first restrike takes place at point *A* at a value close to twice normal voltage. This requires that the dielectric strength of the arc path recovers along some curve such as *I*, that is, along a curve which is above the curve of recovery voltage until at point *A* where they intersect. During the time the arc path is conducting, the dielectric strength of the switch is practically zero. When the arc is again extinguished, the dielectric strength curve again starts from zero but recovers much more rapidly and intersects the curve of recovery voltage at the point *B* causing a second restrike. After the next arc extinction the dielectric strength curve must recover still more rapidly in order to meet the assumed condition that no restrike should occur at the point *C*. These curves show the requirement for the dielectric strength of the arc path to obtain high overvoltages. If curve *I* were not as high as shown, the restrike would have occurred at a lower voltage and the capacitor voltage would not have been as large as shown in figure 4*b*. If the dielectric strength had built up at a more rapid rate, no restrike would have taken place. It can definitely be concluded that the dielectric strength

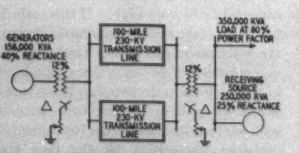


Figure 8. Schematic diagram of system selected for study

Transformer reactance: per cent on 156,000 kva

must build up at a higher rate after any extinction than it did after the preceding extinction in order to develop cumulatively higher voltages. This phenomenon is unlikely to take place in open air between stationary contacts because such an arc path is unlikely to develop the required dielectric recovery strength. In confined arcs, where the pressure may increase after each conduction period, this phenomenon may take place. Separation of breaker contacts will have a tendency to cause higher dielectric strength recovery rates after each conducting period because of the increasingly larger contact separation. These requirements of the arc path probably provide an explanation for the difficulties which have been experienced in attempts to produce high voltages by intermittent arc paths in air over insulator strings. In this connection it may be observed that the conditions for producing high voltages by intermittent arcing are somewhat more favorable for the case of the apparatus failure under oil than for the case of a flashover of an insulator string. The sequences may be for an apparatus failure under oil to cause a line flashover instead of for a line flashover to cause apparatus failure.

The foregoing discussion has been based on simple circuits for the purpose of illustrating the essential element of the theories of intermittent arcing. All actual systems are relatively quite complicated and cannot be reduced to the simple circuits used in the illustrations. Because of this complexity of actual systems it has been found that the maximum voltages with intermittent arcing are not obtained exactly in line with the preceding theories. More specifically, the maximum voltages are obtained for simple

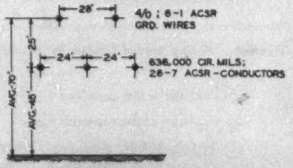


Figure 9. Configuration of transmission line

circuits with the restrikes occurring at either the high-frequency voltage crest or at the fundamental-frequency voltage crest. With complicated circuits it has been found that higher voltages can be obtained by modifying the point of restriking in one direction or the other from these points. This of course is due to the fact that the oscillating circuits have several natural frequencies. The determination of the exact manner of restriking is very difficult to define in analytical fashion. Because of this fact and because of the importance of damping it has been found to be impractical to study arcing grounds and switching transients by the usual methods of mathematical analysis. For this reason it has been found desirable to represent the systems in miniature on the a-c network calculator and to perform the actual switching operations by means of special commutators and this procedure is employed in the study given in part II.

Part II. A-C Network Calculator Study for a Range of Grounding Conditions on a Typical System

In order to study the magnitude and other characteristics of transient voltages produced by switching operations and faults with intermittent arcing, a typical transmission system was selected for a study on the a-c network calculator. Since these transient voltages are greatly influenced by the method of grounding, the neutral impedances of the system were varied through a wide range of resistance and reactance values, between the limits of the solidly grounded system and the ungrounded system.

The principal characteristics of the system selected for study are given in figure 8. This system consists in general of a hydroelectric generating station, the output of which is transmitted 100 miles over 230-kv transmission lines to a load, which is also supplied by local steam generation. The sending and receiving end transformers are considered to be star-connected on the 230-kv side in order to permit grounding, as discussed subsequently. The reactance characteristics of the different parts of the system are shown in figure 8, and the wire sizes and configuration of the transmission lines are shown in figure 9. It is assumed that the transmission lines are separated so there is no mutual effect between them. Also, the generators at both ends of the line are assumed to be in phase and to have the same internal voltage.

The general method used in setting up a problem on the a-c network calculator has been described in a previous paper.[9] In this method the selected system is set up in miniature on a three-phase basis and the circuit changes are accomplished by means of commutators. These commutators are designed to permit close adjustment of opening and closing a circuit or applying or removing a fault. The transient voltages are measured by a cathode-ray oscilloscope from which records on a film can be secured if desired. Because of the large number of circuit changes required for the representation of intermittent arcs to simulate arcing grounds and switching conditions on a system, it became necessary to provide a larger

number of commutators than used in previous studies.[9] Figure 10 shows this equipment together with the measuring and recording apparatus used in the present investigation.

The general method of setting up the network calculator, as previously discussed,[9,10] makes use of equivalent three-phase networks for each circuit element such as machines, transformers, and transmission lines. The character of these equivalent circuits is obvious and requires no comment except for the transmission lines and these are represented by the circuit shown schematically in figure 11.

Figure 10. Switching and recording equipment

Throughout this investigation an attempt is made to obtain the highest voltages for a particular condition. As previously discussed, a slight deviation is made from theories I, II, and III, in order to obtain these voltages. This deviation affects the point at which restriking takes place and this is shifted from the fundamental-frequency voltage crest or the natural-frequency voltage crest to a point to give the maximum transient voltage. In the case of the arcing ground studies the fault is applied at the crest of the normal line-to-ground voltage and is then removed at the first current zero. The point of restriking is adjusted so as to give the maximum voltage for the number of restrikes considered. The fault is always removed at the first current zero following each restrike. In the case of switching operations the circuit is initially opened at a fundamental current zero. The point of restriking is adjusted so as to give the maximum voltage for a given number of restrikes. The subsequent circuit openings are always assumed to take place at the first current zero following the restrike.

In all cases the highest voltages at the point of circuit change are recorded. For example, in the arcing-ground case the voltages are measured at the receiver end. On the other hand, in the case of de-energizing an unfaulted line or the faulted line, the voltages are measured at the sending end, the point at which the switching is actually accomplished. When arcing grounds are considered on the system, several phase voltages as well as the neutral voltage are recorded. In the case of switching operations the voltages are recorded on the phase being switched, both on the line and supply sides as well as across the switch that is opening the circuit.

The voltages recorded are those that take place within $1^1/_2$ cycles from the first interruption considered. In some cases, either on account of system loss or on account of the relation of the natural frequency to the fundamental frequency, higher voltages may be experienced with one or no restrikes than with two or one restrikes, respectively. In some cases, particularly in the Petersen-coil case, the voltages after the $1^1/_2$ cycle period may continue to increase to a steady-state voltage of much higher value. In this connection it should be pointed out that with a Petersen-coil grounded system quite high voltages are obtained if the circuit is in tune at fundamental frequency and a residual voltage is produced as by some unbalance. For example, the opening of one phase of a system subjected to a three-phase or a line-to-line fault on the phase being opened will produce a steady-state voltage of many times normal.

In this investigation of transient overvoltages produced by switching operations and faults, four principal cases have been selected for study as follows:

1. Arcing-ground conditions on one phase to ground.

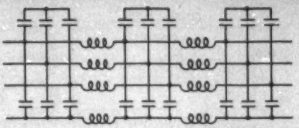


Figure 11. Equivalent network used for representing each 230-kv transmission line of figure 8

2. De-energizing an unfaulted line, one pole unit opening and the other two remaining closed.

3. De-energizing an unfaulted phase with a ground fault on one of the other phases, one pole opening and the other two remaining closed.

4. De-energizing an unfaulted phase with a ground fault on the two other phases, one pole opening and the other two remaining closed.

In general, arcing-ground conditions are for a fault on one phase. De-energizing of a line section is considered more important than energizing because for the latter the intermittent arcing is limited in duration by the closing of the switch. In the case of opening the faulted lines it is assumed that the unfaulted phase opens prior to the pole units of the faulted phase or phases. Such an assumption is based on the ability of the switch to recover dielectric strength at a high rate. This assumption tends to give the higher magnitudes of transient voltage. If the pole unit in the sound phase tends to open after the fault is cleared, then the voltages will be similar to de-energizing an unfaulted line. The voltages will range in values between these limits as the time of relative opening is varied. The conditions selected for study illustrate possible circuit-breaker operations on an actual system.

In this study the transient voltages are obtained for the conditions corresponding to both one and two restrikes. This number of restrikes may be taken as the equivalent of a larger number with the earlier restrikes taking place so quickly that they do not contribute much to the voltage magnitude.

One of the variable factors considered in this study of a typical system is the method of system grounding which includes both resistance and reactance values between the limits of a solidly grounded system and an ungrounded system. When the system is considered solidly grounded, the transformer at the sending end is solidly grounded when one line is considered in operation, and the transformers are solidly grounded at both ends when two lines are in operation. In the case of impedance grounding a reactor or resistor of varying ohmic value is con-

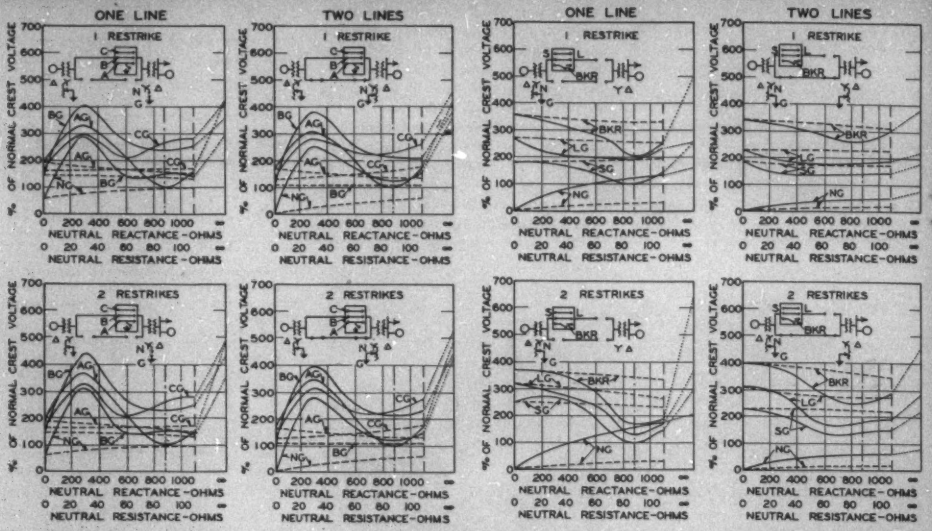


Figure 12. Effect of grounding impedance on transient voltages caused by arcing grounds

Solid curve: reactance grounding

Dotted curve: resistance grounding

Note: Letters on curves refer to lettered points on inset circuit

Petersen-coil reactance: 875 ohms

Figure 13. Effect of grounding impedance on transient voltages caused by de-energizing an unfaulted line

See subcaption of figure 12

sidered in the neutral-to-ground circuit at the sending end when one line is considered in operation, and a reactor or resistor of equal value is considered in the circuit in the sending and receiving ends when two lines are in operation. The ohmic values plotted on the figures to be discussed later are the actual values considered in the ground connection at one point. For example, 50 ohms on a system with one ground point is the value considered in the sending end ground. When two lines are considered in operation, 50 ohms corresponds to the ohmic value in the sending-end neutral connection and a like value in the receiving-end neutral connection.

The results of the a-c network calculator study are presented in graphical form in figures 12 to 15 inclusive. These figures give the transient voltages expressed in percentage of the normal line to ground voltage crest and are plotted as a function of the reactance or resistance in the neutral connection. The solid-line curves are for reactance grounding and the dotted-line curves are for resistance grounding. The value of neutral reactance which corresponds to Petersen-coil grounding is indicated. In each of these figures the data are plotted for one and two lines and one and two restrikes.

Discussion of the Results of A-C Network Calculator Studies

The limited range of previous investigations has made impossible a comparison with the present investigation except for the arcing-ground condition on the ungrounded system. For this case, results of the present study given in figure 12 show maximum voltages on sound phases of 5.2 times normal line to neutral voltage and 4.9 times normal as the corresponding value for the faulted phase. These figures are somewhat higher than the limiting values given by Peters and Slepian[7] for theory II and are comparable with their values for theory III. It is to be noted that the maximum values given in this study are based on two restrikes while the values given by Peters and Slepian are the maximum values for an unlimited number of restrikes. Peters and Slepian concluded from their investigation that the most probable mode for an arcing ground was in accordance with theory II. This conclusion is not contradicted, but the present investigation does establish the fact that higher voltages are possible with intermittent arcing in accordance with modifications of theories I and III.

Figure 12 brings out the fact that high transient voltages may be avoided by the use of the solidly grounded system or the Petersen-coil grounded system, both of which have been employed for many years to avoid the abnormal voltages encountered on ungrounded systems. The voltages corresponding to resistance grounding are of fairly uniform and relatively low value for the range of resistance studied. However, it is to be noted that for high values of neutral resistance approaching infinity, the transient voltage values will approach those of the ungrounded system. The study brings out in striking fashion the fact that there is a value of reactance intermediate between the solidly grounded system and the Petersen-coil grounded system for which the transient voltages are almost as high as with the ungrounded system. This value of neutral reactance is approximately one-third of the Petersen-coil value. A similar relation has been found in a study on a lower-voltage system.

Examination of figure 12 indicates that arc suppression with the Petersen coil may be obtained for some deviation from the tuned value, which is in accordance with operating experience. The voltages on the faulted phase, given in figure 12, for

Petersen-coil grounding, do not show a marked change in magnitude as the reactance is varied in proximity to the tuned value. It is of further interest that the magnitudes of transient voltages are higher for two restrikes than for one restrike, and that there is no appreciable difference between these voltages for one and two lines in service.

The transient voltages resulting from the de-energizing of an unfaulted line are shown in figure 13. The most striking feature of this figure is the fact that the lowest transient voltages, with the exception of those across the neutral impedances, are obtained with Petersen-coil grounding. In all cases the neutral-point voltage increases with increasing values of neutral impedances. For the range of practical values of neutral impedance, there is no appreciable difference between the voltages obtained for the case of one and of two lines. However, in the case of a free neutral system the voltages are appreciably lower for the larger amounts of connected line. Again in these studies it is to be noted that the magnitude of transient voltages increases for both one and two restrikes.

Figure 14 shows the transient voltages for the condition of de-energizing a line section with a fault on a phase other than that which is being switched. It is of interest to note that the voltages in all cases of reactance grounding increase from the solidly grounded case to the free neutral case. The voltages between neutral point and ground also increase for resistance grounding as the magnitude of the resistance is increased. It is to be noted that the voltages for the Petersen-coil grounded system are definitely higher than for any of the lower values of reactance grounding. This is to be contrasted with the dip in the voltage curves of figures 12 and 13. In figure 14 there is a definite increase in the voltages with two restrikes as compared to the case with one restrike. As would be expected, the greater the amount of line connected, the lower the magnitude of the transient voltages encountered.

Figure 15 shows the results of a study similar to that of figure 14 except that a double instead of a single line-to-ground fault is applied to the line section being de-energized. In general, the comments are the same as for the case of figure 14. For reactance grounding the transient voltages increase very rapidly for a relatively small addition of neutral reactance, so that for a very nominal amount of neutral reactance the transient voltages closely approach those of the free neutral system. In this case the voltages experienced with the Petersen-coil grounded system are practically the same as for the free neutral system.

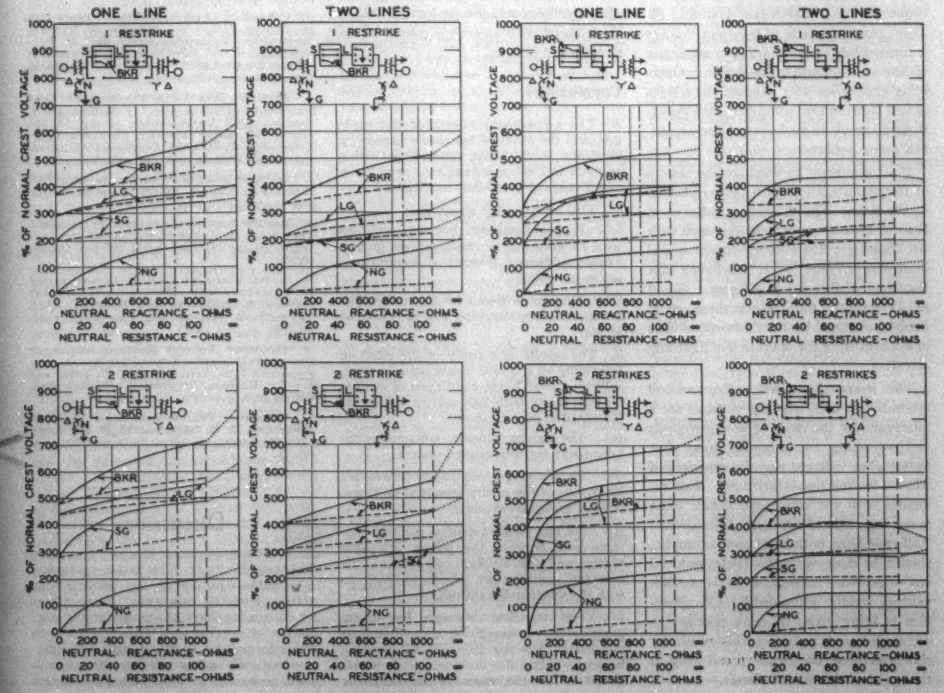
It should be emphasized that the results obtained in the a-c network calculator studies are based on a definite number of restrikes which are spaced at such intervals as to give the maximum voltage for this number of restrikes. Thus, in the average case, since the restrikes may not

Figure 14. Effect of grounding impedance on transient voltages caused by de-energizing line with single line-to-ground fault

See subcaption of figure 12

Figure 15. Effect of grounding impedance on transient voltages caused by de-energizing line with double line-to-ground fault

See subcaption of figure 12



occur at the optimum point, the voltages will be of lower magnitude giving a probability curve for the voltage. It is, of course, appreciated that only a minority of the cases of system faults and switching produce abnormal voltages.

The a-c network calculator studies have also been based on the assumption that the transient voltages of increasing magnitude may be impressed on the system without in any way changing the characteristics of the system. Actually, the transient voltages will be limited by other factors which become of increasing importance as the magnitude of transient voltage increases. On some systems the effect of corona will importantly limit the magnitude of transient voltage by introducing losses in the oscillating circuits. Under some conditions excess voltages will produce increases in exciting current particularly at the lower frequencies, but this factor is ordinarily unimportant. Transient voltages may also be limited by the operation of lightning arresters or protective gaps which are adjusted so as to operate below the flashover level of line or apparatus insulation. The presence of these devices may importantly limit the magnitude of transient voltages encountered on a particular system. Finally, the magnitude of transient voltage is limited by the flashover characteristics of line and apparatus insulation. Operating experience does support the results of this study in that some switching operations do result in flashover of line or neutral point insulation.

It is of interest to compare the results of this investigation with those obtained in the field. The maximum voltages of figures 12 to 15 correspond very well with the limiting voltage of six times normal indicated in figure 1. It is believed that the shape of the curves of figure 1 should not be accepted too freely as these are no doubt influenced by the flashover of lines or apparatus, or the operation of lightning arresters.

The study shows when Petersen-coil grounding is used that the voltages are a minimum for the cases of arcing grounds and switching on unfaulted lines, but that higher voltages may be experienced when a faulted line is switched. This coincides with the conclusion drawn some years ago by Oliver and Eberhardt,[11] "All switching, both hand and automatic, should be done with the (Petersen) coil out of service—namely, with the system neutral solidly grounded." Consideration is being given to relay schemes to accomplish automatically this result by short-circuiting the Petersen coil prior to the opening of a faulted circuit.

That more equipment failures have not occurred may be explained by the fact that the voltages have been limited by flashover at a weak point on the system. This might be at one of several pieces of equipment, or, in most cases, at a lightning arrester that operates. In cases where there is considerable energy in the oscillation, particularly on the larger systems, the phenomenon may even cause the failure of a lightning arrester.

If the maximum voltages appeared on apparatus, it might be severely stressed as the voltages are in excess of the 60-cycle tests applied to apparatus. The severity of this will depend on the breakdown characteristics of apparatus at higher frequencies, a point which needs further investigation.

The results of this study should be of assistance in selecting the voltage class of insulation for the transformer neutral and the Petersen coil. For all cases of switching, the neutral voltages for the ungrounded system are substantially the same as for the Petersen-coil grounded system. However, for the arcing-ground case, the neutral voltages are considerably higher with an ungrounded system than with a Petersen-coil grounded system, although these voltages are less than those experienced with an arcing ground on an ungrounded system.

Conclusions

1. The a-c network calculator has made practical the study of transients caused by switching and faults, including arcing grounds and other intermittent arcs, for a broad range of grounding conditions.

2. This investigation shows that

(*a*). Higher maximum transient voltages may be obtained by modifications of previously advanced theories of intermittent arcing grounds.

(*b*). Theories proposed for arcing grounds are applicable to switching with intermittent arcing.

3. The results of a study of the effect of grounding on a typical transmission system, subjected to different conditions of switching and faults with intermittent arcing, as presented in part II, show:

(*a*). The highest transient voltages are obtained with the ungrounded system.

(*b*). These voltages may largely be avoided by the use of the solidly grounded or Petersen-coil grounded systems.

(*c*). For one value of neutral reactance intermediate between the solidly grounded system and the Petersen-coil system, the transient voltages are about as high as with the ungrounded system.

(*d*). The transient voltages for arcing grounds and de-energizing unfaulted lines are lowest for the Petersen-coil system; however, unless the Petersen coil is short-circuited for the cases of de-energizing faulted lines their transient voltages are relatively high.

(*e*). In general, the lowest transient voltages are obtained with the solidly grounded system.

4. The method of investigation and the results of the study on a particular system are held to be pertinent to the problem of determining the voltage class of neutral point insulation on impedance-grounded systems.

5. The results presented in this study are believed to provide an explanation for some of the line and neutral point flashovers, multiphase faults, and arrester failures that have been experienced on actual systems.

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Discussion

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper represents a valuable addition to the literature on voltage recovery transients. The authors by calculating show the possibility of generation of overvoltages from four to eight times normal due to switching. The question naturally arises whether the assumptions giving rise to these high overvoltages

are valid. The figures given rest upon the premise that two restrikes will take place under the worst possible conditions. If no restrikes occurred, these overvoltages would not be generated. If, on the other hand, more restrikes occurred even higher overvoltages might occur. Citation of a few examples of restriking not accompanied by overvoltages hardly proves that such overvoltages would not occur were the assumptions of the paper not realized. The important conclusion to draw from the paper would therefore seem to be that circuit breakers should be selected which have a minimum tendency to restrike.

C. L. Gilkeson (Edison Electric Institute, New York, N. Y.): The use of the a-c network calculator for studies of transients, as developed by Evans and Monteith, has opened the way to an understanding of hitherto obscure phenomena. The present paper, dealing with the relation between transient overvoltage and neutral impedance, is most interesting. At the same time it emphasizes the need for more knowledge in other related fields in order that the significance of the paper may be properly evaluated.

In the discussion of figure 7, the authors have clearly stated the characteristics of the dielectric recovery in the arc, with respect to the recovery voltage, which permits the production of voltages of the type they are here discussing, namely, that the dielectric strength increases between successive restriking of the arc. It seems reasonable to find that such a condition does exist in a circuit breaker, where the length of the restriking path increases with time. Arcs across insulators would not be expected to have such characteristics. A question of importance is whether faults in confined space, such as cable failures, bushing failures, or arcs under oil, in expulsion tubes, or expulsion fuses may have such characteristics. If the condition in the arc, necessary to cause high transient voltages, can occur only during the opening of a breaker the problem takes on one aspect, since its duration is limited, however, if it may occur during an arc in a confined space the problem takes on an entirely different aspect.

In the study of overvoltages, conducted by the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell System, a number of records have been obtained for faults in confined spaces, such as cable failures, bushing failures, and arcs under oil. These records were obtained from operating systems and were for the most part from automatic magnetic oscillographs, supplemented in one case by an automatic cathode-ray oscillograph. The systems included an extensive 140-kv isolated neutral system, a 140-kv system equipped with Petersen coils, a 26-kv system with a 75-ohm neutral resistor, and a 44-kv system with a 150-ohm neutral resistor. For faults in confined space, many of the records showed that during a part of the disturbance, the arc was extinguished and restruck, every half cycle, every cycle, or at irregular intervals. In all cases the restrike appeared to be controlled by the fundamental-frequency voltage, occurring at or near the crest of the voltage wave. In no case did the restrike occur at a higher voltage than the normal crest value. In most cases the extinction of the arc appeared to take place at the current zero of fundamental frequency but in some cases at a current zero of higher frequency. An oscillogram illustrating the conditions for a fault in a confined space is given in a paper by Jeanne and Gilkeson, AIEE TRANSACTIONS, volume 53, 1934.

There have been a few instances where intermittent extinction and restriking of an arc might have been associated with an arc in open air. However, the condition is so rare that it is probable that if all the facts were known it would have been found that these few cases were also associated with faults in confined space.

To summarize the results of these observations, it appears that intermittent arcing of the type discussed does not occur across insulators in open air but may occur for arcs in confined space. While the data do not indicate an increase in dielectric strength between successive arcs they do not preclude this possibility. A study of the dielectric recovery for arcs in confined space, such as cables or bushings or in expulsion tubes or fuses, appears to be warranted.

A point of considerable interest in the paper is the relation between overvoltage and neutral impedance. One important conclusion of the paper is that under certain conditions a Petersen-coil system, badly out of tune, might be subjected to very high transient overvoltage. However, for moderate values of neutral impedance, 100 ohms resistance (the maximum considered in this paper), or 100 ohms reactance, the curves of figures 12 to 15 indicate that the overvoltage is little different from the condition of no impedance in the neutral. It should be recognized that a 100-ohm neutral impedance, on the 230-kv system represented, is equivalent to a much lower impedance on a system operated at a lower voltage.

Figure 14 shows an overvoltage of about 4.4 times normal, for a solidly grounded neutral for two restrikes on a single line. This value of overvoltage is near the upper value of overvoltages recorded for switching surges, and helps to explain why there is no consistent relationship between the observed switching transients and the method of operating the system, whether with impedance in the neutral or solidly grounded.

P. A. Jeanne (Bell Telephone Laboratories, Inc., New York, N. Y.): Due to my contact with the study of problems involved in fault-current limitation, I have found the papers relating to transient overvoltage, presented at this session, most interesting. The authors deserve a great deal of credit for their contributions to a difficult subject. My comments, while presented specifically in connection with the Evans, Monteith, and Witzke paper, also refer in general to the other papers on this subject. Mr. Gilkeson in his discussion, has referred to the data on overvoltages obtained by the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell System which tend to substantiate the idea expressed in the Evans, Monteith, and Witzke paper that an arc in air is unlikely to go through the sequence of extinction and restriking required for the cumulative building up of overvoltage according to the arcing-ground theory. I want to add a few comments based on these same data. The oscillograms from the resistance grounded systems and isolated system, referred to by Mr. Gilkeson, confirmed the possibility of some restriking during the opening of breakers which clear a faulted line. For the systems studied, the restriking appeared to be confined to the faulty phase, and usually occurred before the recovery voltage had reached a value equivalent to the crest of the normal-frequency wave. The resulting overvoltage on the sound phases following the restriking did not exceed that to be expected from the simple initiating transient.

An examination of the oscillograms of breaker-cleared two-phase-to-ground faults obtained from the Petersen-coil system over a period of five years showed overvoltages of about the same magnitude as those from the one line-to-ground self-cleared faults, indicating that the clearing sequence requisite for producing the higher voltages is likely to be of very infrequent occurrence.

With regard to the Clarke, Crary, and Peterson paper, I should say that the oscillograph observations tend to substantiate the conclusion reached therein, namely, that the maximum voltage generally will be in the order of that determined by the simple initiating or clearing transient. This was the order of magnitude of the maximum voltage recorded by oscillographs capable of recording up to around 3,000 cycles. Surge recorders, where used, tended to indicate considerably higher maximum voltages than the oscillographs, except in one case where a capacitance-coupling potentiometer in place of the usual string-insulator potentiometer was used to connect the surge recorder to the line. Since many of the surge-recorder records include the effect of lightning, as well as the transients due to a fault itself, it has been found difficult to determine correctly the magnitude of the overvoltage due to the fault alone. By discounting portions of a surge-recorder figure which appeared to be due to lightning or similar steep-wave-front phenomena, it was found that the maximum voltages deduced from the surge recorders tended to be from 30 to 40 per cent higher than shown by the oscillographs. It seems difficult to reconcile these differences, particularly as in a recent installation a good check between a magnetic oscillograph, a cathode-ray oscillograph, and a surge recorder, was obtained on the system where the capacitance potentiometer was employed to couple the latter two types of instruments to the line.

These papers indicate a marked advance in the analytical and laboratory testing technique for determining overvoltages. On the basis of these studies it should be possible to choose a system or systems having the characteristics most likely to contribute to high overvoltage, install automatic cathode-ray oscillographs, and determine whether the high voltages are realized.

C. Concordia, E. M. Hunter, and H. A. Peterson (all of General Electric Company, Schenectady, N. Y.): During about the last 20 years, many papers discussing the effects of restriking of the arc in a fault or interrupting device have appeared. Some of these have presented test results, but most have proposed theories which

could be fully developed and applied only in an approximate form. In addition, the fundamental assumptions of these theories regarding system behavior were on a rather insecure basis. The present paper is particularly valuable since it corrects the first fault mentioned above and presents the results of a following out of a physically consistent restriking procedure, with damping taken properly into account.

The second item of whether or not the assumptions are sufficiently representative must be determined by comparison with operating experience and with test results. However, at least one of the assumptions (that, in case of clearing of faulted lines, one of the unfaulted phases clears first) appears very likely to be correct except in the case of single-line-to-ground faults on systems grounded through Petersen coils. In such systems, for line-to-ground faults, breaker action should not ordinarily be required at all because clearing should be accomplished by the Petersen coil. In case the fault is a solid one, and breaker action is required, the faulted phase might clear first. If the faulted phase does clear first in the particular system investigated, voltage will not be built up across the switch to any great degree for either resistance or reactance grounding, and voltages on the unfaulted phases will also be much lower than for interruption of the unfaulted phases. The reason for this is evident when the natural frequency or frequencies of oscillation of the system investigated are considered. For low natural frequencies it is not possible to build up high voltages due to restriking in the faulted phase because of the limited number of restriking-reclearing cyles that can take place before the fundamental component of voltage (which is the changing axis of oscillation of the natural-frequency components) passes through zero. In fact, if the natural frequencies are sufficiently low, the magnitude of the recovery voltage across the breaker following the first restrike and reclearing may be even lower than that following interruption at normal current zero.

The condition of restriking at the maximum point of each preceding recovery-voltage wave is of course seldom realized in practice. Instead, with certain types of interrupting devices, restriking might occur at lower voltages, but on the other hand, might continue for several cycles, with all phases restriking in case of interruption of line charging current. The magnitudes of voltage indicated by the curves of this paper are thus to be considered primarily as indications of the *relative* severity of different methods of grounding. Similar restriking studies which we have made on systems indicate that the voltages are about the same for either resistance or reactance grounding of the same ohmic magnitude, except for the dip in the curves with reactance grounding for certain cases.

It is important to bear in mind also that the results of this investigation apply only to a specific system. Similar switching procedure carried out on different systems has indicated that, in particular, neutral voltages are considerably affected by the amount of capacitance interrupted relative to the total system capacitance.

The authors conclude that all switching on Petersen-coil systems should be done with the Petersen coil short-circuited, and state that this conclusion is in agreement with that of J. M. Oliver and W. W. Eberhardt (authors' reference 11). It should be pointed out that the overvoltages discussed by Oliver and Eberhardt arose chiefly from series resonance. This source of overvoltage has been effectively reduced, in all subsequent Petersen-coil installations, by the use of iron cores instead of the air-core reactors used in Oliver and Eberhardt's application. Moreover, in the operating experiences to date on 22 applications of coils in the United States, extending over several years of operation, there has, to our knowledge, so far been no indications of dangerous overvoltages.

E. W. Knapp (The Shawinigan Water and Power Company, Montreal, Que., Canada): The papers which have been presented are of special interest to the power company operating long high-voltage transmission lines. It might be of interest to mention at this time a few instances of overvoltage during switching. The system under consideration consists of a double-circuit steel-tower line with metallic bussing at the receiving end only. The lines are 135 miles in length and operate at 165 kv. The insulation consists of 10 and 12 units; there are two overhead ground wires and some buried counterpoise. At the receiving end of the line there is an automatic oscillograph with a sensitivity of about 5,000 cycles. Voltage records are taken from line potential transformers and current records are taken from bushing-type current transformers on the line oil switches.

During the past few years there have been recorded a number of cases of momentary overvoltage. In some cases the sound line became involved at about the time that the initially faulted line cleared. In one case during 1938 during a line-to-ground fault on phase *C*, voltages of 425 kv and 660 kv crest were recorded on phases *B* and *A* to ground, respectively. In another case during a line-line-to-ground fault on *B* and *C* phases, successive increases of voltage occurred on phase *A* until a crest value of 720 kv was reached before either flashover or clearance. Both of these troubles were during lightning and both lines were eventually involved.

Perhaps the most interesting operation occurred due to a piece of wire creating a line-to-ground fault on phase *B* on one line about 18 miles from the receiving end. At the instant of clearing at the receiving end, a crest voltage of 320 kv was recorded on phase *C* which flashed over. The sending end of the line was cleared a few cycles later throwing 174,000 kw on to the sound line. The faulted line was then automatically returned to service with practically no loss of load and without additional flashover. There was no lightning during this trouble.

R. D. Evans, A. C. Monteith, and R. L. Witzke: Mr. Prince has commented on the assumptions on which our study of transient voltages due to switching operations were based. He has indicated that if there are more than two restrikes higher transient voltages than those given in the paper might be encountered. The magnitude of transient voltages to be expected is not to be increased in direct proportion to the number of restrikes that take place. While several restrikes may take place, the effect on the transient voltages as indicated by klydonograph studies will not exceed that of two restrikes occurring at such intervals as to produce maximum cumulative action. This is due to several factors including the probable sequence of opening of the pole units in an actual breaker, as pointed out in the paper. The spacing between restrikes is fully as important as the number of restrikes and it is misleading to consider the total number of restrikes alone since without proper spacing the action will not become cumulative.

Mr. Prince has also raised the question as to the characteristics of breakers that are desirable from the standpoint of minimizing transient overvoltages. If restriking is wholly avoided, cumulative action is prevented. However, it is undesirable for a breaker to have such characteristics as to force current zero or such as to operate with a high extinction voltage. High dielectric recovery strength, low extinction voltage, and nonforcing of current zero are, to an extent, conflicting considering the full operating range of a breaker. In the present state of the art the emphasis, in our opinion, should be placed on the circuit condition. The principal significance of our paper has to do with the selection of the circuit condition for minimizing transient voltage, as for example, by the use of a solidly-grounded instead of a reactance-grounded system, etc.

Gilkeson and Jeanne have reviewed the work on transient overvoltages which has been done by the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell Telephone System. This work has been of great value and confirms the thought expressed in our paper that arcs over insulators in air rarely produce transient overvoltages, but that the conditions of arcing in a confined space, as for example, in the failure of bushings or cable insulation, are more favorable for cumulative action by intermittent arcs.

Mr. Gilkeson has commented on the fact that the records obtained on cable and bushing failure showed intermittent arcing with restrikes occurring every half cycle, every cycle, or at intervals, but that these do not show that restriking has taken place at greater than normal voltage. However, it is to be noted that the dielectric recovery characteristic of the arc path varies from a value such that breakdown occurs at normal voltage or less when the arc restrikes every half cycle, to a value which is nearly twice normal voltage for the condition in which the arc is interrupted at a current zero and restrike does not take place within a half cycle. Thus the dielectric recovery strength varies from a value somewhat less to a value somewhat more than that necessary to produce cumulative action. This would mean that there should be a tendency under some conditions to start cumulative action. Mr. Gilkeson has pointed out that evidence of this action has not been obtained although the data does not "preclude the possibility of such action."

Mr. Gilkeson has also pointed out that the condition for cumulative action is of very short duration if it arises from a switching operation but may be of long duration if it arises from an intermittent arc or incipient

Influence of Resistance on Switching Transients

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pacitive a-c circuits. Typical simple circuits are assumed and the transients corresponding to various values of resistance are shown as curves. They demonstrate clearly the effect of resistance on switching transients.

The transients are described for single-phase circuits having a voltage source uninfluenced by the transients.

THE voltage recovery transient appearing across the terminals of a circuit-interrupting device has been the subject of numerous studies during the past ten years. Their importance has justified these studies because they determine in part the severity of the duty impressed upon circuit-interrupting devices. These studies have consisted of mathematical analyses of circuit conditions, calculating board investigations and studies of oscillographic records of the actual transients, as they are obtained on systems and in high-power laboratories.[1]

The damping of the voltage recovery transient, is a function of the resistance of the circuit. It depends not upon the absolute value of the resistance, but upon the value of the resistance relative to the inductances and capacitances. Important variations in the transients can be produced by changing the values of the resistances.

For the consideration of complicated systems, use may be made of the a-c network calculator as discussed in another paper, "Power-System Transients Caused by Switching and Faults" by Messrs. Evans, Monteith, and Witzke (AIEE TRANSACTIONS, volume 58, 1939, pages 386–97). The calculating board can be set up to represent the capacitance and inductance relations and if these are chosen with proper respect to the resistances of the circuit, an approximation of the damping will be obtained.

In mathematical studies, the inductances and capacitances of the various parts of the circuit are determined or estimated and from them the voltage recovery transients are calculated. Except in cases more simple than are usually encountered in system studies, the resistances of the circuits cannot be included because of the added complication of the mathematical expressions. Consequently, the rate of damping of the transient is assumed on the basis of experience and a general knowledge of the effect of resistance is essential in these studies.

The damping of voltage recovery transients can be studied in relatively simple circuits which contain resistance, inductance, and capacitance. These transients can be calculated and the rate of damping determined. The mathematical expressions for these circuits are relatively complicated but a graphical representation of the transients can be used to demonstrate the relations.

This paper presents graphically the effects of resistance on the closing and opening transients of inductive and capacitive a-c circuits.

Paper number 39-51, recommended by the AIEE committees on power transmission and distribution, and protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted November 9, 1938; made available for preprinting January 3, 1939.

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1. See bibliography at end of paper.

Closing Transients of Inductive Circuits

When an a-c circuit containing resistance and inductive reactance is closed by a switch or when the resistance or reactance is altered, the steady-state condition of the system is changed and usually a current transient exists before the new steady-state is established. This is caused by the difference in magnitude of the instantaneous values of the steady-state currents before and after the instant the switch is closed. Since the current in the circuit cannot change instantly to the new value, a transient current component of amplitude equal to the difference is superimposed on the new steady-state current and decays as an exponential function of time. Such transient currents are shown in figure 1 and figure 2 and can be expressed by equation 1 given in the appendix.

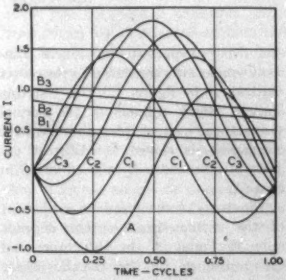

Figure 1. Effect of time of closing on asymmetry of current in an inductive circuit

If a circuit is closed at a time corresponding to a normal current zero, current is established without any transient as shown in figure 1 by the curve marked *A*. This current is symmetrical and contains no transient component. (Transients in the symmetrical component of current due to demagnetization of the generators are not considered in this paper.)

When the contacts close at a time other than a normal current zero, a transient component of current flows

fault in a cable or other confined space.

Concerning the discussion by Concordia, Hunter, and Peterson, it is to be pointed out that from the standpoint of overvoltages produced by switching on the Petersen-coil-equipped system as discussed in the paper, there would be no appreciable difference caused by the substitution of an iron-core reactor for an air-core reactor. This is due to the fact that the magnitude of overvoltage produced by switching with intermittent arcing is not critical with respect to the tuned value of Petersen-coil reactance.

This method of producing overvoltages with a Petersen-coil system is not to be confused with that involving resonance. The latter effect was encountered in the investigations reported in the paper for certain fault and unbalanced circuit conditions such as produced by the opening of a breaker pole. In a symmetrical system high voltages should not be produced by series resonant action except as a result of some switching operation. Since switching operations may in themselves produce high transient voltages as a result of intermittent arcing it is not necessary, as Concordia, Hunter, and Peterson have done, to postulate both a switching operation and a series resonance for the unbalanced condition to account for high transient voltages.

E. E. Knapp has cited a case in which transient voltages greater than those corresponding to a simple break have been experienced. This supports the assumptions made in the study reported in our paper.

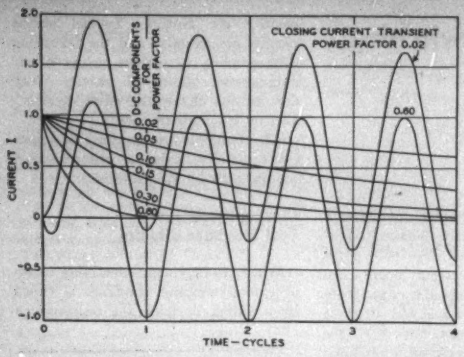

Figure 2. Effect of power factor on d-c component of closing current transient

and decays exponentially. These transient components are shown by the curves marked *B* in figure 1. The resulting current, which consists of the normal symmetrical current plus the transient component, is shown for different degrees of asymmetry by the curves *C* in figure 1.

The decay of the transient component of the asymmetrical current depends upon the value of the inductance and the resistance of the circuit. These same two elements, the resistance and inductance, determine the power factor of the circuit. Consequently the decay of the d-c component varies with the power factor of the circuit. The higher the resistance relative to the inductance; the higher the power factor of the circuit and the more rapidly the transient component decreases. This is shown in figure 2. The d-c components for fully asymmetrical waves are plotted for circuits having power factors from 0.02 to 0.60. The total currents including both the a-c components and the d-c components are plotted for two power factors. These curves show that in circuits having a low power factor, the asymmetry of the current will be maintained for a relatively long time. This becomes important in some current transformer and relay applications, because of possible saturation of the magnetic circuit. At the other extreme, the transients decay very rapidly; at 60 per cent power factor, the transients disappear at the end of one cycle.

These relations are important in the application and testing of circuit breakers. A high-speed circuit breaker operating on a low-power-factor circuit will interrupt the circuit before the d-c component has disappeared. A circuit breaker operating on a higher-power-factor circuit, opening after several cycles due to a relay timing or slower mechanical action will open only symmetrical currents.

The international rules for high-voltage circuit-breaker testing are based largely on the performance of circuit breakers that do not open until the d-c component has disappeared. Consequently, for 80 per cent of the tests demonstrating rupturing capacity they specify that the current shall have a direct component not greater than 20 per cent of the crest value of the alternating component. On test circuits having very low power factors, this value is not obtained until 10 to 14 cycles after the beginning of the short circuit. The curves in figure 2 show that by inserting additional resistance in the test circuit to raise the power factor to the maximum permitted by the rules (0.15) the time required to reach 20 per cent asymmetry can be reduced to only 1.6 cycles. A brief duration of the short circuit during testing is desirable because it minimizes the demagnetizing effect and results in less decay of the alternating component of current and in a higher restored voltage.

Testing under American rules is conducted with both symmetrical and asymmetrical currents up to the breaker rating or over the range of power available. Consequently in American laboratories, low circuit resistance is desirable to give a slowly decreasing d-c component.

Closing Transients on Capacitive Circuits

When a capacitive circuit is energized by the closing of a circuit breaker, a transient occurs which can cause an overvoltage on the system. The capacitance, if composed of relatively short cables or lines, so that the inductance is negligible, can be assumed to be lumped. The circuit which energizes it will have inductance, resistance, and capacitance. In the circuit shown in figure 3*a* it is assumed that the capacitance, *C*, to be energized is lumped and the capacitance, C_1 of the rest of the circuit is negligible.

When the arc strikes, the voltage at the switch will become ground potential and a voltage drop will appear across the inductance because the capacitance *C* is assumed to be uncharged and at ground potential. The inductance and capacitance of the circuit, connected by the striking of the arc, produce an oscillation with a possible crest value equal to twice the normal crest voltage. The resistance damps this circuit but its effectiveness depends upon its magnitude relative to L/C. The voltage recovery

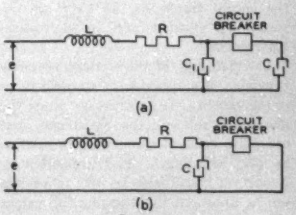

Figure 3

(*a*)—Energizing a capacitive circuit
(*b*)—Opening a simple inductive circuit

transient for several values of resistance are plotted in figure 4. The smallest value of *R* is comparable with those obtained in high-power laboratories. For resistance values less than the critical resistance, $R = 2\sqrt{L/C}$, the voltage transient is defined by equations of damped oscillations. For resistance values greater than the critical value, the voltage transients are defined by exponential equations and curves. The equations of these transients are numbers 2, 3, and 4 of the appendix.

In the closing of a high-voltage circuit by a conventional circuit breaker, the arc will strike before the contacts touch and the arc resistance will exert some damping effect on the transient. However, even with the maximum crest occurring with minimum damping, no dangerous voltage would be impressed on the system by the closing transient of this type.

In the curves of figure 4 it has been assumed that C_1 was negligible with respect to *C*. This causes the voltage transient to start at zero because the ca-

pacitance C is uncharged at the beginning of the transient. If C_1 is large enough to raise the potential of the capacitance C when the two are connected together by the closing of the breaker, the transient will start not from zero but from the potential taken by the capacitances. The amplitude of the transient is no longer the system potential at the time the arc strikes, E_m, but is the difference between E_m and the potential of the capacitors. The capacitance used in the formula for determining the transient is, of course, the sum of the capacitances C and C_1.

During the closing of a high-voltage breaker, it is possible for the arc to be extinguished and to restrike before the breaker is completely closed. This phenomenon may produce higher voltages because the line may be charged to a high potential by the first transient and

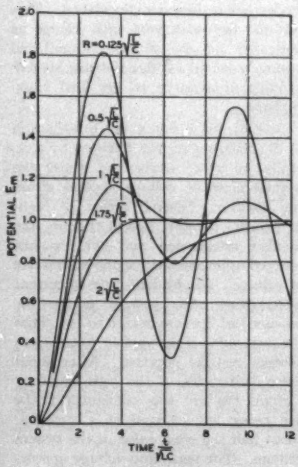

Figure 4. Voltage transients

Closing of capacitive circuit
Opening of inductive circuit

the amplitude of the second transient be increased thereby. However, the conditions on closing are not favorable for the building up of high overvoltages since the gap between contacts is becoming smaller. The phenomena is the same during the interruption of charging currents and more favorable conditions exist when the contacts are separating. Therefore this phenomenon will be described in connection with the interruption of charging currents.

When the capacitance is distributed over a long line it cannot be represented as a single lumped capacitance and more complicated circuits must be used. The principles are the same but the possible combinations are too numerous to consider here.

Opening Transients of Inductive Circuits

The opening of a short circuit or the opening of the circuit energizing an unloaded transformer may be considered as the opening of an inductive circuit. These currents lag the applied voltage by relatively large angles and consequently the voltage appearing across the contacts after the interruption is approximately the crest value of the applied voltage. The small capacitances of the circuit, which play no part in determining the current, are important in determining the voltage recovery transient. Likewise, the resistance of the circuit, which was negligible while the current was flowing, damps the voltage recovery transient. The resistance may be a small parallel load which is not removed by the opening of the circuit breaker or may be due to the resistivity of the conductors forming the circuit.

Series Resistance

Figure 3*b* represents a simple series circuit involving inductance, capacitance, and resistance. Frequently, this circuit is a part of a more complicated circuit and can be considered as a unit in itself independent of the rest of the circuit. The opening of this circuit is mathematically the same as the closing of a capacitive circuit, figure 3*a* and equations 2, 3, and 4. It has voltage recovery transients which are shown in figure 4. When the curves are applied to voltage recovery transients following the opening of a reactive circuit, the time scale will generally represent a shorter interval because the capacitance between the breaker and the inductance usually will be much smaller than the line or load capacitance.

For high-power laboratory circuits having relatively low resistance with respect to the inductance, the damping of the oscillation corresponds roughly with the curve for $R = 0.125\sqrt{L/C}$. Similar system circuits could be expected to have similar transients.

Combination of Series and Shunt Resistance

The opening of a circuit by a switch may not completely unload the source, or a circuit breaker may open in two steps, the first one inserting a resistance for limiting the current. Circuits of these types are represented by the diagram in figure 5.

This circuit too may be oscillatory or nonoscillatory depending upon the circuit constants. The critical condition is

$$\frac{R}{L} - \frac{1}{R_1 C} = \frac{2}{\sqrt{LC}}$$

The transients are similar to those shown in figure 4 for the simple series circuit.

The equations applying to this circuit are numbers 5, 6, and 7 in the appendix. The curves indicate and the equations show that the voltage transients occurring during the opening of an inductive circuit cannot attain potentials above two times the normal crest value of voltage.

General

The effects of an arc voltage prior to the last current zero and of the extinction of an arc before the normal current zero have been neglected but are important in reactive circuits. Both of these phenomena increase the amplitude of the transient and tend to raise the potential at the crest. Therefore, the maximum voltage which can be reached depends upon the characteristics of the circuit breaker and upon the circuit. A review of a large number of oscillograms of single-phase interrupting tests on high-voltage circuits showed no voltage in excess of 2.75 times the crest value of line-to-ground voltage and only a few reached 2.25 times.

Opening Transients of Capacitive Circuits

The interruption of a capacitive circuit would take place without a transient if the circuit had no inductance and no resistance, if the arc was extinguished at current zero, and if the dielectric strength of the point of interruption increased to a little more than twice the crest of the applied voltage in a half cycle of the system frequency. A negligibly small transient occurs if the dielectric-strength

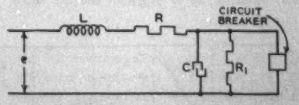

Figure 5. Opening a simple inductive circuit having both series and shunt resistance

condition is fulfilled. On high-voltage circuits, such high dielectric strength is very difficult to obtain at the first current zero so the arc usually restrikes. The restriking initiates a transient which may produce high overvoltages. The circuit and the transients following a restrike are shown in figure 6.

Normally, the resistance is relatively low and the transients, both current and voltage, are oscillatory. On the first restrike, the current will pass through zero at times other than the normal current zero and if extinguished, may leave the capacitance charged to a voltage either above or below the applied voltage. With no resistance in the circuit and the worst possible rate of increase of dielectric strength, the theoretical rate of increase in voltage at successive restrikes would give 1, 3, 5, etc., times the normal crest of system voltage as shown in figure 7. However, this required that the gap after the first interruption (*a*) holds while the voltage across it increases from zero up to twice the normal crest (*a* to *b*), that it breaks down at this value and after a half-cycle of the transient interrupts again (*c*). If the breaker opening leaves the line charged as at *c*, the potential on the source side of the breaker will tend to return to the value of the applied voltage. It will do this through a transient similar to that which occurs on the opening of an inductive circuit, namely a damped oscillation produced by the inductance of the supply circuit and the capacitance still connected to it. This transient is damped by the resistance of the circuit but will reach a value approximately as shown at *d* and impress nearly four times normal crest voltage on the gap. As this transient dies (*d* to *f*) the voltage returns to approximately two times the crest value and increases due to change in the applied voltage from approximately two times to four times the crest value. This is reached at point *g*. To continue the building up of voltage, the arc must now restrike at *g* with little more voltage on it than it had at the point *d*.

Obviously this dielectric performance is almost, if not quite, impossible. Oscillographic data of actual interruptions by circuit breakers show a much more gradual build-up of voltage. In some cases, the breakdowns occur before the crest value of voltage is reached so that the amplitudes of the intermediate transients (*b* to *c*) are reduced. In other cases, the transient current may not be extinguished at its first current zero. If the current flows for two half-cycles of the high-frequency transient, the voltage on the line is reduced to a very low value. The damping of the transient by the resistance of the arc and of the metal conductors in the circuit also tends to reduce the rate of voltage build-up.

The influence of these modifying factors is shown by the oscillograms reproduced in figure 8. These oscillograms were taken during the interruption of capacitive currents in a high-power laboratory. In an oscillogram the line *A* represents the voltage across the terminals of the breaker, the line *B* the current flowing in the circuit, the line *C* the trip-coil current, and the line *D* the voltage on the source side of the breaker. Due to the circuit used, the oscillations in the voltage *D* are a maximum. The large capacitance representing the line was disconnected from the low capacitance of the source. Consequently, on a restrike, the amplitudes are not reduced by the equalization of potentials between them.

Oscillogram *a* shows the interruption of the charging current without any restriking. The voltage appearing across the breaker contacts was approximately two times the crest value of the applied voltage but the arc space did not break down.

Oscillogram *b* shows one restrike after a current pause during which the voltage rose to approximately 25 per cent of the crest value. The restrike was extinguished after a half-cycle of the high-frequency current. The arc did not restrike subsequently although the value of voltage appearing across the breaker contacts was approximately 1.7 times the crest value of the applied voltage.

Oscillogram *c* shows a restrike at a voltage approximating 50 per cent of the crest value of the applied voltage and the extinction after a half-cycle of the high-frequency current. This extinction occurred at approximately a normal voltage zero so that the subsequent voltage applied across the terminals of the breaker did not exceed the normal 60-cycle voltage. The arc did not again restrike.

Oscillogram *d* shows a restrike after approximately one half-cycle of restored voltage during which the potential applied across the breaker increased to approximately two times the crest value of the system voltage. The high-frequency current flowed for three half-cycles before it was extinguished. This left the line with very little charge as indicated by the almost symmetrical voltage wave appearing across the breaker contacts subsequent to the final interruption.

Oscillogram *e* shows the interruption of the charging current followed by a restrike at very nearly two times the normal crest of voltage applied across the breaker. Several cycles of high-frequency current flowed before the breaker interrupted and left the line charged approximately at the crest value of voltage. After a half-cycle of current interruption, the voltage across the breaker had again increased to two times the crest value of the applied voltage, and another restrike occurred. After about seven half-cycles of the high-frequency current, the arc was extinguished, the line being left charged at a potential about half the crest value of the system voltage. The maximum voltage appearing across the breaker subsequent to the final interruption was approximately $1^1/_2$ times the crest value of the system voltage.

Oscillogram *f* shows the best example of building up of voltage across the terminals of the breaker. Three restrikes occurred and on the last interruption, the line was left charged to about 1.85 times the normal line-to-ground voltage and during the subsequent half-cycle of restored voltage, the potential difference across the breaker increased to about 2.85 times the normal line-to-ground voltage.

On a 220-kv system where it was suspected that the interruption of line charging current was producing excessive

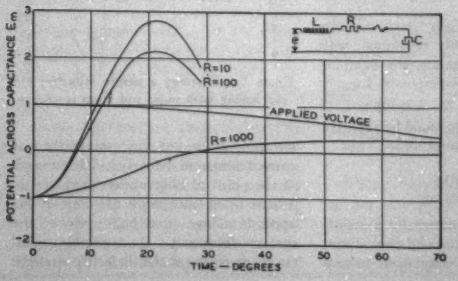

Figure 6. Restriking at crest of voltage wave with capacitance charged to potential of the previous crest

Curves show the effect of resistance on the transient voltage across the capacitance

L = 0.1 henry

$C = 10^{-4}$ farads

overvoltages, tests were made recently with a cathode-ray oscillograph recording the line voltage. Sections of lines up to 246.4 miles were disconnected and the maximum voltage recorded was 2.43 times the crest value of the system line-to-ground voltage. These voltages are harmless and indicate that on a typical system the high overvoltages obtained theoretically by neglecting the dielectric characteristics of the breaker, are seldom encountered.

Resistors in Circuit Breakers

Because of the effects of resistance on switching transients, circuit breakers using resistors have been built for many years. In Europe, prior to 1930, oil circuit breakers either plain-break or explosion-pot types sometimes had auxiliary contacts which inserted a resistance between terminals. The auxiliary contacts closed before and opened after the main or arcing contacts. Due to the relatively short gap between the arcing contacts when the auxiliary contacts were just touching, the probability of the resistance functioning to facilitate opening of the circuit was remote and their main service was in reducing the severity of the transients which occur on closing capacitive and transformer circuits. These resistances damped the inrush current to lines and limited the inrush current when a transformer was energized. The advantages gained hardly justified the additional complication and they disappeared from the market.

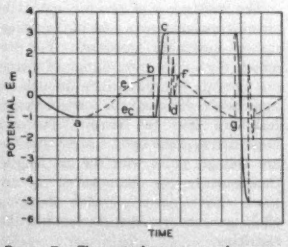

Figure 7. Theoretical transient voltages appearing at the two terminals of a circuit breaker during the interruption of a capacitive current

e = Voltage at the terminal connected to the source

e_c = Voltage at the terminal connected to the capacitance being disconnected

Note the transient c-d-f following a restrike which impresses almost as much voltage across the circuit breaker as the normal cyclic voltage change f to g

Some modern interrupters are being built with resistors which aid not only in closing circuits but also in the extinction of arcs. They facilitate the interruption of both charging current and reactive current. The resistors damp the transients which occur during the interruption of leading currents and reduce the overvoltages produced. They are generally inserted by being connected across either a part of the gap formed by the arcing contacts or a separate gap. The insertion of the resistor increases the power factor of the circuit, shifts the current zero to a point in the cycle where the applied voltage is less, and reduces the overvoltages which can occur on the system.

In lower-voltage circuits where heavy currents are the problem, resistors are used to facilitate the interruption of short-circuit currents and thereby increase the interrupting ability of the circuit breakers. An arc inserts the resistance which reduces the current, increases its power factor, and thus brings the short circuit within the limits which can be interrupted directly by the arc extinguishing means provided for the complete opening of the circuit.

The value of the resistance used depends upon the rated voltage and the rated rupturing capacity of the breaker. The magnitude of the voltage appearing across the gap which inserts the resistance depends upon the system voltage, the reactance of the circuit, and the resistance. The relations are given in the appendix as equation 8. These relations are demonstrated by figure 9 with voltage plotted for values of r/x of 0.1, 1, and 10. With $r/x = 0.1$ the voltage appears across the resistance and arc gaps at a very low rate and reaches only a low maximum value. The arc could be easily extinguished but the resistance makes only $^1/_2$ per cent difference in the total impedance of the circuit and consequently does not aid to any measurable extent in the ultimate interruption of the circuit.

With $r/x = 1$ the voltage appears more rapidly and reaches a value of about 50 per cent of the applied crest on the first peak. The second peak, a half-cycle later and consequently less important, reaches 70 per cent.

With $r/x = 10$ the transient component decreases very rapidly and disappears in about 20 degrees. The voltage rises rapidly across the resistance and inserting gap but does not exceed the crest value of applied voltage.

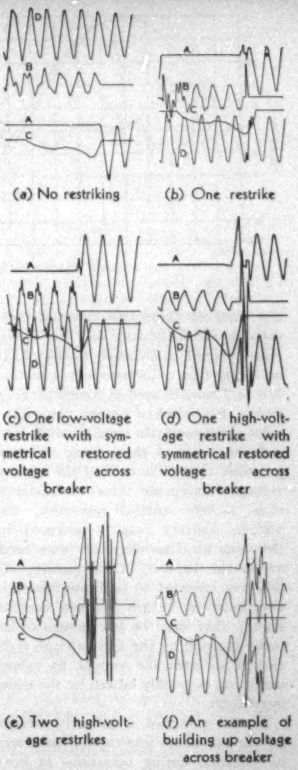
A
B
C
D
(a) No restriking
(b) One restrike
(c) One low-voltage restrike with symmetrical restored voltage across breaker
(d) One high-voltage restrike with symmetrical restored voltage across breaker
(e) Two high-voltage restrikes
(f) An example of building up voltage across breaker

Figure 8. Typical oscillograms of the interruption of charging current at about 22 kv in a high-power laboratory

A—Voltage across breaker
B—Current
C—Trip-coil current
D—Voltage line-to-ground on supply side

Note that none of the oscillograms show the theoretical rate of voltage increase given in figure 7

The impedance of the circuit would be increased about ten times and consequently the current to be interrupted by the second gap is reduced to about ten per cent of the full short-circuit current.

Still further reduction in the current can be obtained by higher values of r/x. However, the effect of capacitance across the gap becomes important when the current flowing through the resistor becomes comparable with the current required to charge the capacitance.

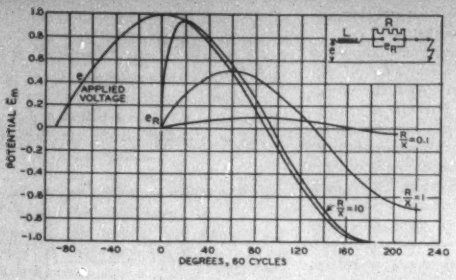

Figure 9. Voltage transients across a gap inserting resistance in an inductive circuit

The sum of these two currents flows through the inductance and the conditions upon which equation 8 is based are no longer true. Consequently, equation 5, 6, or 7 must be used to express the relations. For values of r above the critical value of resistance, the circuit is oscillatory and the crests of the voltage recovery transient exceed the crest of the applied voltage. Except for values of resistance close to the critical resistance, the voltage recovery rate is substantially the same as if no resistance were used across the breaker. Consequently, resistances intended to facilitate interruption must be chosen between definite limits; they must be low enough to be easily inserted by the first gap and high enough to limit the current to values which can be readily broken by the main interrupter.

If the resistance is properly chosen for the maximum interrupting capacity, its insertion during operations at currents below the rated interrupting capacity cause no more difficult conditions because r/x is smaller and the voltages across the resistance are lower. For low currents at higher power factors the voltage drop across the resistor is only a fraction of the drop across the total circuit resistance.

The resistor may be inserted by an arc rupturing device having a high arc voltage, which effects the transfer during the course of the cycle rather than at the current zero. As soon as voltage appears across the connections to the resistor a part of the current is transferred to the resistor. An arc voltage maintained higher than the voltage drop in the resistor will result in the transfer of all the current from the arc, without waiting for an arc-current zero.

The resistor makes the final circuit much easier to interrupt. That high-power-factor circuits are easily opened is generally known. Typical transients showing why this is true are given in figure 10 for various values of r/x from 0.125 to 2. All the curves are drawn for the same values of L and C which have been assumed very large. The transients have a natural frequency of only 900 cycles per second and are spread sufficiently to be easily studied. These curves show clearly that the insertion of a resistor in a reactive circuit reduces the crest value of the transient and also the voltage recovery rate and consequently facilitates the interruption.

The interrupting performance of a resistance-inserting breaker is practically independent of the severity of the circuit recovery-voltage characteristics because the voltage transients across its contacts are controlled largely by the resistor.

With charging currents the resistor can reduce the magnitude of the overvoltages which occur during interruption. The resistor may be inserted by a high arc drop in a manner similar to that on an inductive circuit. If it is inserted at a current zero, the voltage which appears across the parallel gap increases slowly and to a magnitude determined by the relation of the resistance to the inductance and the capacitance of the circuit. If inadequate gap is available a restrike will occur. After the resistance is inserted, the capacitance is charged through the resistor and the voltage of the capacitance is lower than the applied voltage. Any restrike across the second gap occurring before adequate contact separation is obtained will be through the resistor and will be damped by it. Thus the resistor facilitates the extinction of charging currents by reducing the voltage of the capacitance and by damping transients if they occur. Consequently, the resistor reduces the overvoltages which can occur.

Except when the resistor provides the cheapest means of increasing the upper limit of the interrupting ability of a circuit breaking device, its complication is undesirable. Usually, the extension of existing designs will produce a simpler and cheaper means of obtaining the desired interrupting ability.

Arc Resistances in Circuit Breakers

The resistances of the arc spaces in circuit breakers play a part in the damping of switching transients. For example, during the interruption of charging current, the arc strikes through an appreciable distance and introduces arc resistance into the circuit. The arc resistance depends upon current and the arc voltage varies with the arc length. Consequently, the resistance of the arc space exerts an appreciable damping effect upon the transient produced by the restriking.

That the resistance of the arc space may be sufficiently low to influence the voltage recovery transient on inductive circuits was demonstrated in a paper presented before the Institute in 1933. The demonstration that current flowed through these arc spaces during the recovery transient was based upon cathode-ray oscillograms. Four oscillograms were shown which gave approximately the same range and type of transients as those represented in figure 4 of this paper. The transients were not exactly

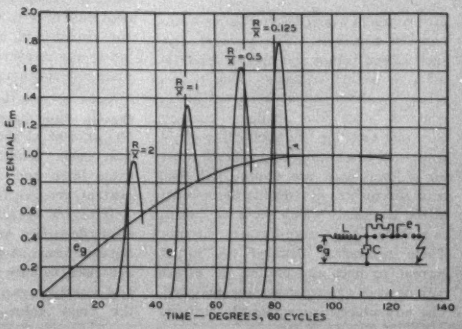

Figure 10. Voltage transients on a gap interrupting an inductive circuit into which a resistance has been inserted

the same however, since the resistances producing the damping were variable instead of constant.

Summary

An inspection of switching transients shows that the resistances of the circuits play an important part in limiting the amplitudes and the durations. Although only a few typical circuits have been analyzed, the general damping effect of resistance has been shown. The calculation of more complicated circuits becomes extremely difficult if the resistances, reactances, and capacitances are all considered. Consequently, calculations of more complicated circuits generally are limited to a consideration of the inductances and capacitances only. The damping of the transients is not included in the calculations and approximations for them have to be made. It is believed that the charts presented in this paper will help in choosing suitable damping factors.

In the design of circuit breakers resistors can be used to increase the interrupting ability of the circuit breaker at the expense of simplicity in construction.

The resistances of the arc spaces of circuit breakers can appreciably influence switching transients by increasing the damping of the circuit.

Appendix

The equations given below are the basis for the curves in the illustrations.

Closing Transients of Inductive Circuits

$$i = \frac{E_m}{Z}\left\{\cos(\theta-\theta_0-\theta_1) - \left[\cos(\theta_0+\theta_1) - \frac{i_0 z}{E_m}\right]\epsilon^{-\frac{r}{x}\theta}\right\} \quad (1)$$

E_m = crest value of applied voltage
i_0 = i for $\theta = 0$, the start of the transient
r, x, and z are the resistance, reactance, and impedance of the circuit
θ_0 = phase angle of voltage at $\theta = 0$
$\theta_1 = \tan^{-1}\frac{x}{r}$

Closing Transients on Capacitive Circuits and Opening Transients on Inductive Circuits

For $R > 2\sqrt{L/C}$

$$e = E_m\left\{1 - \frac{LC}{\sqrt{R^2C^2-4LC}}\times(n_1\epsilon^{-m_1 t} - m_1\epsilon^{-n_1 t})\right\} \quad (2)$$

$$m_1 = \frac{RC+\sqrt{R^2C^2-4LC}}{2LC}$$

$$n_1 = \frac{RC-\sqrt{R^2C^2-4LC}}{2LC}$$

For $R = 2\sqrt{L/C}$

$$e = E_m\left\{1-\left(1-\frac{Rt}{2L}\right)\epsilon^{-\frac{Rt}{2L}}\right\} \quad (3)$$

For $R < 2\sqrt{L/C}$

$$e = E_m\left\{1 - \frac{2\sqrt{LC}\epsilon^{-\frac{Rt}{2L}}}{\sqrt{4LC-R^2C^2}}\times\sin\left(\frac{\sqrt{4LC-R^2C^2}}{2LC}t + \tan^{-1}\frac{\sqrt{4LC-R^2C^2}}{RC}\right)\right\} \quad (4)$$

Opening Transients of Inductive Circuits Having Both Series and Shunt Resistances

For $\frac{R}{L} - \frac{1}{R_1C} < \frac{2}{\sqrt{LC}}$

$$e = E_m R_1\left\{\epsilon^{-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_1C}\right)t}(A_1\sin bt + B_1\cos bt) + C_1\cos(\omega t+\alpha)\right\} \quad (5)$$

$$A_1 = \frac{C_1}{b}\left[\omega\sin\alpha - \frac{1}{2}\left(\frac{R}{L}-\frac{1}{R_1C}\right)\cos\alpha\right]$$

$$B_1 = -C_1\cos\alpha$$

$$C_1 = \sqrt{\frac{1+R_1^2\omega^2C^2}{(RR_1^2\omega^2C^2+R+R_1)^2 + \omega^2(R_1^2\omega^2C^2L + L - R_1^2C)^2}}$$

$$b = \frac{\sqrt{4LC-\left(\frac{L}{R_1}-RC\right)^2}}{2LC}$$

$$\theta = \tan^{-1}\frac{\omega L}{R} + \frac{3\pi}{2} \text{ or } \tan^{-1} - \frac{R}{\omega L}$$

$$\psi = \tan^{-1}\frac{\omega L(R_1^2\omega^2C^2+1) - R_1^2\omega C}{R(R_1^2\omega^2C^2+1)+R_1}$$

$$\gamma = \tan^{-1}\omega CR_1$$

$$\alpha = \theta - \psi - \gamma$$

For $\frac{R}{L} - \frac{1}{R_1C} > \frac{2}{\sqrt{LC}}$

$$e = E_m R_1 C_1\left\{\epsilon^{-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{CR_1}\right)t}\times(D_1\epsilon^{ft} + D_2\epsilon^{-ft}) + \cos(\omega t+\alpha)\right\} \quad (6)$$

$$D_1 = \frac{1}{2f}\left\{\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{CR_1}\right)-f\right]\times\cos\alpha - \omega\sin\alpha\right\}$$

$$D_2 = -D_1 - \cos\alpha$$

$$f = \sqrt{\frac{(L-RR_1C)^2 - 4LCR_1^2}{2LCR_1}}$$

For $\frac{R}{L} - \frac{1}{R_1C} = \frac{2}{\sqrt{LC}}$

$$e = E_m R_1 C_1\left[\epsilon^{-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{CR_1}\right)}\times\left\{\left[\omega\sin\alpha - \frac{1}{2}\left(\frac{R}{L}+\frac{1}{CR_1}\right)\cos\alpha\right]t - \cos\alpha\right\} + \cos(\omega t+\alpha)\right] \quad (7)$$

The voltage across a gap inserting a resistor in an inductive circuit, figure 9, is given by equation 8. This equation assumes that the resistance-inserting gap is an arc-rupturing device which has a negligible arc voltage and which interrupts at a normal current zero.

$$e = \frac{E_m r}{x\sqrt{1-\left(\frac{r}{x}\right)^2}}\times\left[\cos\left(\theta-\theta_1-\cot^{-1}\frac{r}{x}\right) - \epsilon^{-\frac{r}{x}\theta}\cos\left(\theta_1-\cot^{-1}\frac{r}{x}\right)\right]$$

E_m is the crest value of the 60-cycle voltage wave

$\frac{r}{x}$ is the ratio of the resistance and reactance of the circuit

θ_1 is the phase of the applied voltage at the start of the transient

If the extinction voltage is not negligible an additional term is inserted after $\cos\left(\theta_1 - \cot^{-1}\frac{r}{x}\right)$.

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Discussion

W. F. Skeats (General Electric Company, Philadelphia, Pa.): Mr. Van Sickle is to be congratulated upon the clarity of his exposition of the subject. Undoubtedly many will obtain a much clearer understanding of the influence of resistance from reading this paper.

A warning must be sounded, however, with reference to connecting too closely the rate of decay of the d-c component of short-circuit currents with the power factor. The resistance influencing the former is substantially the d-c resistance of the circuit, whereas the resistance involved in the latter is the a-c resistance and may be considerably higher. Similarly the resistance involved in the damping of the higher-frequency oscillations which occur upon interruption of a circuit, is likely to be considerably greater than the normal-frequency resistance, and must be so in order to bring about the damping that is observed.

It is also easy to make a mistake in the consideration of load resistance. A synchronous motor, for instance, even though it may be operating at unity power factor must be represented for consideration of transients not as a resistance, but as the combination of a reactance and a generating source. Lighting and heating loads are pure resistance but may not be very effective for damping because of the reactance of transformers and other apparatus which must in general be connected between these loads and the circuit breaker.

Mr. Van Sickle's statement at the end of the section on "Opening Transients of Capacitive Circuits," "These voltages are harmless and indicate that on a typical system the high overvoltages obtained theoretically by neglecting the dielectric characteristics of the breaker, are seldom encountered," seems contradictory to conclusion 5 of the paper by Messrs. Evans, Monteith, and Witzke (AIEE TRANSACTIONS, volume 58, 1939, pages 386–97) which, after a discussion of overvoltages based on only a slight modification of the theory discussed by Mr. Van Sickle, reads, "The results presented in this study are believed to provide an explanation for some of the line and neutral point flashovers . . . that have been experienced on actual systems."

R. D. Evans, A. C. Monteith, and R. L. Witzke (all of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): When considering the broad subject of switching transients, it is always of interest to compare field tests with the analytical results. Mr. Van Sickle has included test data of the line-to-ground voltage for the condition of opening charging currents on a 230-kv solidly grounded system. The oscillogram to which Mr. Van Sickle refers shows seven restrikes and a maximum voltage of about 250 per cent of normal crest. The voltage obtained falls in the range for similar conditions given in figure 13 of our present paper (AIEE TRANSACTIONS, volume 58, 1939, pages 386–97) which shows 230 per cent for one restrike and 320 per cent for two restrikes. In considering this comparison it is to be noted that the system under test was of considerable greater total mileage but that only one-third of total was deenergized by the switching operation. These figures are in reasonable agreement and emphasize the statement in our paper that there may be a large number of restrikes in the actual case of interrupting the circuit but only a limited number are significant in producing the overvoltage.

(See also discussion, page 412.)

R. C. Van Sickle: Mr. Skeats brought out a very valuable point in emphasizing the need for choosing the correct values of inductance and resistance in the analysis of circuit transients. The values used should be those which correspond to the frequencies of the transient.

In the discussion of the closing transients of inductive circuits, the decay of the d-c component is given as a function of the power factor of the circuit. The frequencies of the transients were 60 cycles or less and the assumption was made that the values of the resistances and inductances were the same for both components of the transients. This is a good approximation not only for the simple single-phase circuit which was discussed but also for three-phase circuits. The International Electrotechnical Commission Publication No. 56 "I.E.C. Specification for Alternating Current Circuit Breakers," uses the same assumptions in an appendix which gives a method of determining the short-circuit power factor of a test from the decay of the d-c component.

When a more exact determination is desired, both the resistance and the inductance values should be taken more accurately.

The difference in the 60-cycle resistance and the d-c resistance will be determined largely by the skin effect in the larger conductors of the circuit. In parts of the circuit such as the bus structure this may make a 15 or 20 per cent difference but for the entire circuit only a much smaller increase would be expected.

The values of the inductances determining the a-c and d-c components are not the same. The d-c component depends upon the negative-sequence reactance. The a-c component depends upon the direct-axis reactance, and in the simple circuit discussed in the paper, it was assumed constant.

Mr. Monteith and Mr. Evans have shown the agreement of this paper with theirs.

Power-System Voltage-Recovery Characteristics

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ASSOCIATE AIEE

WITH the increased use of protector tubes, a thorough knowledge of the recovery voltages to which they may be subjected has become highly desirable. The current range over which a tube can be expected to function successfully is necessarily dependent on the voltage recovery characteristics of the system in which the tube is applied. Since many systems have a large range of fault currents for the different fault and system conditions, it is essential that the corresponding voltage recovery characteristics be carefully considered. This paper presents the results of an investigation to determine and evaluate the importance of the factors which influence the voltage recovery characteristics of power systems. A very large number of tests were made on a specially designed miniature equivalent circuit representing a transmission line, connected apparatus, and the fault-clearing device. In that a miniature system was used, this investigation is similar to that made by Messrs. Evans and Monteith and presented in two recent papers.[1,2] The results presented in this paper represent refinements and extensions to the understanding of the phenomena which will be of interest to both designers and users of protector tubes or other fault-clearing devices. Factors which have not been evaluated previously are shown to influence the phenomena considerably.

Special electronic devices were developed for the purpose of applying and removing the fault in synchronism with the source voltage. These devices have inherent characteristics which closely simulate the arc voltage characteristics of protector tubes.

The point on the voltage wave corresponding to the instant of application of the fault, is shown to be very significant under certain conditions. When this is varied, results obtained indicate the indefiniteness of a first crest in the transient voltage recovery characteristics and point to the maximum crest, time to maximum crest, and the initial recovery rate as being more descriptive.

In the case of double-line-to-ground faults, the conditions under which they would be most likely to occur on an actual system are considered.[5] The effect of this consideration, and the effect of restriking of the first tube attempting to clear are illustrated. Misleading results are shown to be obtainable if these considerations are neglected.

Generalized results are presented in a form such that they can be applied to any solidly grounded system operating between 13.8 and 138 kv.

Conclusions

1. Different angles of fault application materially affect system voltage recovery characteristics. When this factor is considered, the significance of a first crest is lost in many cases, and the results indicate that time to maximum crest and maximum crest voltage are the main system voltage recovery characteristics which lend themselves to summarization. Initial rate of rise of recovery voltage is important, but since it varies greatly with fault location in a given system, no attempt is made to summarize the results obtained for the initial period. Instead, a method of calculating the maximum initial rate of voltage rise is indicated which is adequate for many cases. It should not be inferred from this that the events taking place during the interval of time up to voltage crest are unimportant in the functioning of the tube. Actually, the entire voltage recovery characteristic is important up to the time of maximum voltage reached.

2. In studying double-line-to-ground-fault recovery voltages, the probable angle of fault occurrence in an actual system must be considered. Under certain conditions, much more severe recovery voltages can be obtained in a controlled setup than are likely to be obtained in an actual system. It seems evident that if a tube can interrupt a single-line-to-ground fault in a solidly grounded system where tower-footing resistance is encountered, it generally will be able to interrupt a double-line-to-ground fault.

3. Crest recovery voltages obtained in the solidly grounded systems investigated varied from 1.5 to 1.75 when tower-footing resistance was neglected. The effect of losses in the system (including tower-footing resistance) is to decrease the overshoot for single-line-to-ground faults. It appears that 1.75 is near an upper limit which may be reached in higher-voltage systems while 1.5 would be more likely to be reached in a lower-voltage system. This is in general agreement with field tests and theoretical considerations. It should be recognized, however, that system loads and interconnections generally would tend to reduce slightly the maximum overvoltage reached in an actual case.

4. Neutral grounding resistance produces a decrease in maximum overshoot in a manner very similar to that produced by tower-footing resistance.

5. Neutral grounding reactance increases the time to crest, since the zero-sequence frequency is reduced as more reactance is added in the neutral. The effect upon the crest voltage reached appears to depend greatly upon the length of line involved.

6. The magnitude of the arc voltage corresponding to the arc voltage across the protector tube (over a practical range) appears to have little effect upon the voltage recovery characteristics.

7. Length of line, system voltage, and fault current all play an important part as shown in figure 8 of this paper. It is expected that this information will be helpful as an aid to the proper selection of tubes for solidly grounded systems.

8. The results of this investigation appear to be in general agreement with those published by Messrs. Evans and Monteith,[1,2] although, since the systems studied were different in the two investigations, direct comparisons are difficult to make.

9. While this investigation has been chiefly concerned with recovery voltages obtained when faults are interrupted by protector tubes, it is felt that some of these results may be of value to designers and users of other fault clearing devices as well. The flexibility of a miniature setup of this type with the advantages of electronic switching devices has been, and promises to continue to be, helpful in arriving at a better understanding of numerous closely related phenomena.

Equipment Used

The equivalent system used to represent the transmission line was specially designed for this investigation.[6] This made possible the use of units having characteristics simulating those of an actual transmission line over the desired range of frequencies. One factor which influences the phenomena quite appreciably is the resistance-frequency characteristic of the units representing the transmission line.[7] A three-phase equivalent π section as used in this study representing ten miles of typical line is shown in figure 1. This

Paper number 39-49, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted October 26, 1938; made available for preprinting January 3, 1939.

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The author acknowledges the helpful suggestions of Edith Clarke and S. B. Crary and C. Concordia, which have contributed to the success of this investigation. Acknowledgment is also made of S. B. Farnham's assistance in making many of the laboratory tests.

1. For all numbered references, see list at end of paper.

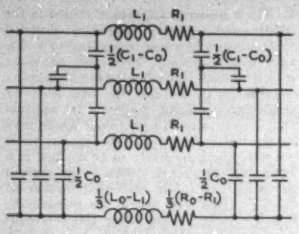


Figure 1. Artificial-line-section connections

is similar to the circuit used in obtaining the results of references 1 and 2.

Source reactances were simulated by means of reactors having the desired characteristics. Transformers were used as shown in figure 2 to make it possible to have a low ratio of X_s/X_1 at the source when desired.

Electronic switching circuits were developed for applying the fault at any desired point on the voltage wave and for interrupting the current or currents at or near the normal current zero. The operation of these circuits is described in the appendix. The circuit used to apply and remove single-line-to-ground faults is shown in figure 3. Use of the thyratron tube to carry the fault current made it possible to represent quite accurately the arc voltage inherent in the protector tube.[4] By variation of the constants, the circuit can be adjusted to apply the fault at intervals of from one to about six cycles, the allowable frequency of repetition depending upon the amount of damping in the circuit under investigation. Once the frequency of fault application has been selected, the phase-shifter can be rotated to vary the point of application of the fault on the voltage wave throughout the range of probable occurrence in an actual system. Thus the effect of point of application of the fault could be investigated easily with this circuit since the thyratron interrupts the fault current automatically at the first subsequent current zero regardless of when the fault occurred. This factor was found to be of particular significance under certain system and fault conditions. The magnitude of the arc voltage could be varied at will by inserting a storage battery in series with the thyratron.

The circuit for studying double-line-to-ground faults is shown in figure 4. A third unit can be incorporated to investigate three-phase faults.

Under some conditions in studying the double-line-to-ground fault, it was desirable to simulate the restriking of the first phase attempting to clear. This was accomplished by means of utilizing a synchronous switch to carry the first loop of current and transferring to the tube on the last loop. A circuit used to accomplish this is shown in figure 5.

A three-phase 110-volt 60-cycle, sine-wave generator was used to energize the miniature system. This was of sufficient capacity so that voltage at its terminals remained essentially constant regardless of transient disturbances imposed in the circuits. Thus auxiliary equipment could be energized from the same source, thereby providing the necessary means for synchronization of fault application.

To observe the transient recovery voltages, an oscilloscope was used. This afforded a convenient means for observing the repeated transient since the

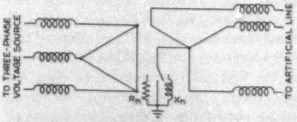


Figure 2. Equivalent circuit for source reactances

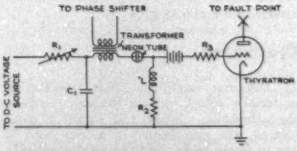


Figure 3. Recurring-fault circuit used in studying transient recovery voltages following single-line-to-ground faults

image could be made to appear stationary on the screen. Time exposure photographs could be taken of this image if desired. However, it was found more practical to take actual measurements directly off the calibrated screen of the oscilloscope.

Discussion of Results

In discussing transient recovery voltages which occur when fault currents are interrupted by protector tubes, it should be emphasized that generally there are two basic differences between these voltages and those obtained in circuit-breaker operation. In the first place, as has been pointed out elsewhere,[1,3,4] protector-tube recovery voltages are generally of a slower nature than those very fast ones sometimes obtained in a circuit-breaker operation which severs one part of a system from another.

As a second point of difference, it should be noted that circuit-breaker interruptions more often occur from a steady-state condition of fault current while a protector tube interrupts generally from a transient condition. Ordinarily a circuit breaker is called upon to operate after fault current has been flowing for several cycles which is of sufficient duration for the natural frequencies to disappear from the fault current and for the d-c offset to be greatly reduced. Protector tubes usually operate in a single half cycle, and therefore, in many cases the natural frequency oscillations in the fault current may not be damped out when interruption takes place. The amount of this transient disturbance present (and also the amount of d-c offset) for a given case is a function of the point on the voltage wave at which the fault occurs.

The inherent flexibility which the fault-simulating circuit possesses made it possible to investigate the effect of fault angle. Figure 6*a* shows several single-line-to-ground-fault recovery voltage transients, each one for a particular value of the angle of fault application as indicated. The fault angle is designated as θ_A which is so defined that a value of

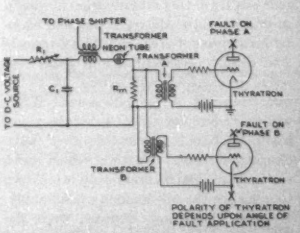


Figure 4. Recurring-fault circuit used in studying transient recovery voltages following double-line-to-ground faults

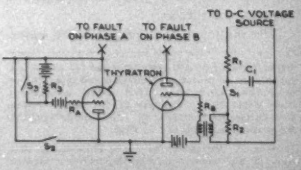


Figure 5. Recurring-fault circuit used in studying transient recovery voltages following double-line-to-ground faults

S_1, S_2, and S_3 are synchronous mechanical switches. Phase *A* carries two loops of fault current and phase *B* carries one

θ_A = 90 degrees corresponds to the time at which the steady-state voltage on phase A is a maximum, the single-line-to-ground fault always being applied on phase A. Values of θ_A from 0–90 degrees indicate application of the fault before voltage crest is reached, while values of θ_A from 90 degrees – 180 degrees indicate application of the fault after the voltage crest. Figure 6*c* shows the crest values of the curves in 6*a* plotted as a function of θ_A. The maximum crest recovery voltage was obtained for θ_A = 78 degrees. In this case, line losses were high enough so that the natural-frequency oscillations in the fault current were damped out before interruption took place.

Figure 6*b* shows several recovery voltage transients as obtained on the miniature system representing 100 miles of low-loss line and source reactances as indicated. In figure 6*d* the crest values reached in figure 6*b* are plotted as a function of θ_A. For this case, the maximum recovery voltage of 1.7 was reached for either of two values of θ_A, namely 88 degrees and 120 degrees, while in between these two peaks lies a low value of 1.2 at 108 degrees. This characteristic of alternate peaks and valleys in the crest recovery voltage versus θ_A curve is particularly marked in the case of low-loss lines and for low values of fault current.

From observations of the transient fault current, it was possible to associate these peaks and valleys with the oscillations in the fault current which were of a frequency essentially inversely proportional to the length of line represented in the miniature system. Corresponding field tests indicate that this frequency corresponds to the frequency with which a voltage (or current) surge travels four times over the line length involved.[3] The number of such traversals which can take place during the time that the fault is on is a function of the angle at which the fault is applied. Further analysis indicated that each peak of recovery voltage in figure 6*d* could be associated with fault-current interruption at an instant of minimum rate of change of fault current, and each valley with interruption at a maximum rate of change of fault current. Also, since initial rate of rise of recovery voltage is proportional to the rate of change of fault current just prior to interruption, it was possible to associate a maximum initial rate of rise with fault interruption at a maximum rate of change of current and a minimum initial rate of rise with fault interruption at a minimum rate of change of current. If a system has losses low enough so that these fault-current natural-frequency oscillations exist when the first normal current zero is reached, these alternate peaks and valleys in the crest recovery voltage versus θ_A curve will occur.

The significance of the curves of figure 6 is that in general it is necessary to determine a recovery voltage envelope obtained by applying the fault over a range of values of θ_A. It is conceivable that a single-line-to-ground fault could occur for any value of θ_A between 0 and 180 degrees. However, it has been found that the recovery-voltage envelope is generally determined by values of θ_A between 70 degrees and 110 degrees approximately.

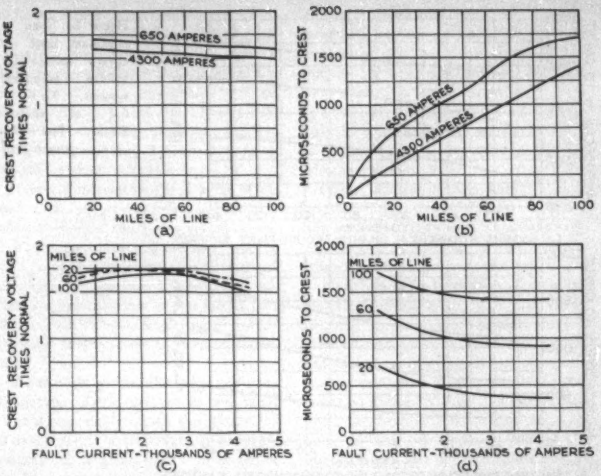
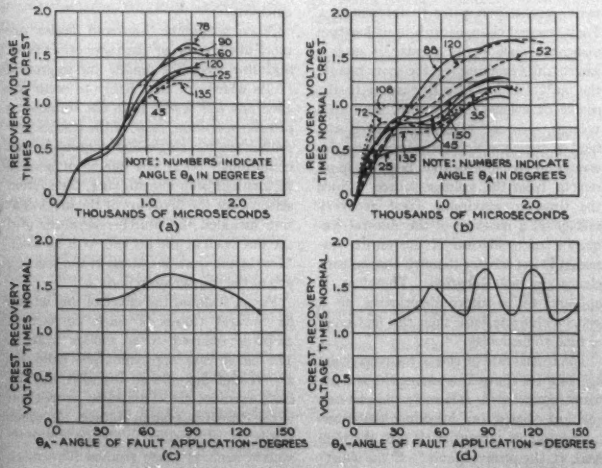


Figure 7. Effect of line length and fault current on recovery voltage. X_0/X_1 = 0.4 at source. Currents are root-mean-square symmetrical values for line-to-ground fault in 115-kv system

Figure 6. Effect of fault angle on recovery voltage. X_0/X_1 = 0.4 at source supplying 650 amperes root-mean-square symmetrical line-to-ground fault current in 115-kv system

(*a*) and (*c*)—60 miles of high-loss line

(*b*) and (*d*)—100 miles of low-loss line



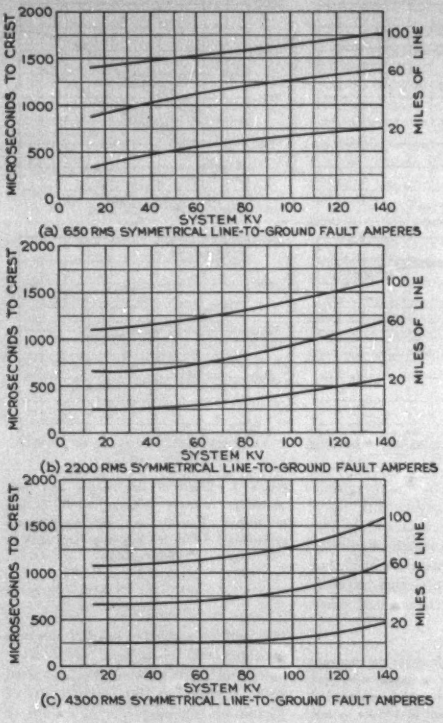


Figure 8. Time to maximum crest recovery voltage for solidly grounded systems. $X_0/X_1 = 0.4$ at source. Single - line - to-ground fault

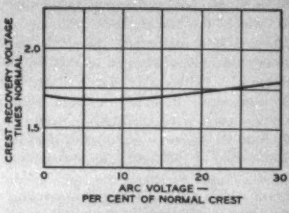


Figure 9. Effect of arc voltage. $X_0/X_1 = 0.4$ at source. One hundred miles of line. Six hundred fifty amperes root-mean-square symmetrical line-to-ground fault current in 115-kv system at source

When all possible angles are considered, in many cases the identity of a first crest is lost in a more or less smooth envelope rising to a maximum crest value of recovery voltage at a definite time for a given case.

The entire recovery-voltage envelope is of importance, and for successful operation it is essential that the recovery dielectric strength within the tube should be greater at all times than the voltage recovery characteristics. Since it is difficult to summarize recovery characteristics during the initial period, only the maximum crest value in the recovery-voltage envelope and the time required to reach this value are indicated in the summary of results.

There is another reason for using only the maximum crest value reached as an indication of the severity of recovery voltage. It was found that the initial period of recovery voltage is quite definitely a function of fault location along the line while the maximum crest voltage reached and the time to maximum crest voltage were not greatly affected by fault location. The reason for this is that the initial transient period following interruption is governed by the rate of change of fault current just prior to interruption. Fault current changes with fault location along the line, being greater if near a source and becoming less the more remote the fault location is with respect to the source of voltage. Therefore, the initial voltage recovery rate is greater if the fault is near the voltage source, and decreases as the fault location becomes more remote from the voltage source. Since the time to maximum crest recovery voltage is a measure of the natural frequency of oscillation of the entire system, it is not subject to much change with change in fault location. Therefore, it appears to be more descriptive as a system characteristic than the first crest or time to first crest.

The initial rate of rise of recovery voltage can be approximately evaluated for many cases by a relatively simple calculation, based on injecting the symmetrical fault current back into the network at the point of fault.[8] If the short-circuit current at any point along a line is known, then the initial rate of rise is

$$IZ\omega \times 10^{-6} \text{ volts per microsecond}$$

where

I = crest value of the symmetrical fault current
$\omega = 2\pi f$ (f is system frequency)
Z = surge impedance viewed from the fault point

The initial rate of rise calculated from this expression is the maximum that can be obtained (neglecting natural-frequency components in the fault current) since a symmetrical current wave is assumed. For any instant of fault occurrence which would give a d-c offset component in the fault current, the initial rate would be less. For any system having low losses such that the natural-frequency oscillations would not be damped out when interruption occurred, the maximum initial rate would be higher. In such cases, the maximum initial rate would be difficult to calculate.

Since single-line-to-ground faults are more likely to occur than any other type, and also, since the double-line-to-ground faults which are most likely to occur are generally less severe from the standpoint of tube operation, most of the results presented are for single-line-to-ground-fault conditions. After the effects of several factors had been investigated, the system selected for the first part of the investigation included the source reactances and the line open at the far end with no load. Most of the work was done at the sending end of the transmission line.

Figure 7 shows the effect of line length for several values of fault current in amperes referred to a 115-kv system. The curves are approximately valid for a system of any voltage provided that the fault currents are changed in proportion to the change in system voltage. In other words, it is possible to define a simple system such as these studied here more

generally in terms of X_1 and X_0 at the source, but it is believed that the results are of more significance when plotted with amperes as a parameter. The results indicate that lower currents and shorter line lengths at a given system voltage tend to give higher crest values of recovery voltage in solidly grounded systems. Time to crest increases with line length. This can be explained by the fact that voltage reflections from the far end of the line return less frequently than for shorter lengths and therefore a longer time is required for this building up process. Higher currents reduce the time to crest since the short-circuit current in the miniature systems studied is a measure of source reactance. An increase in current is associated with a decrease in source reactance, which in turn increases the natural frequency of the system and consequently results in a shorter time to crest voltage when interruption takes place.

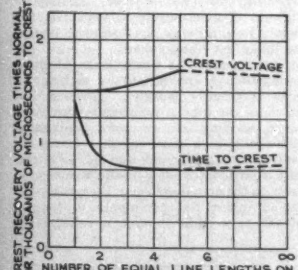

CREST RECOVERY VOLTAGE TIMES NORMAL OR THOUSANDS OF MICROSECONDS TO CREST
CREST VOLTAGE
TIME TO CREST
NUMBER OF EQUAL LINE LENGTHS ON COMMON BUS—TOTAL 100 MILES

Figure 10. Effect of line grouping. X_0/X_1 = 0.4 at source. Four thousand three hundred amperes root-mean-square symmetrical line-to-ground fault current in 115-kv system at source

Figure 8 is a more comprehensive summary of results obtained for various lengths of line, for various system voltages, and for three values of fault current. These curves are of importance in that they show clearly the effect of varying any one of the three factors. The curves are valid for the relatively simple solidly grounded systems studied, but the qualitative effects of the factors involved can be shown to be valid in general for the more complicated systems on which tubes may be desired. Therefore, this summary may be considered a guide to proper selection of protector tubes. Crest recovery voltages are not summarized since tests indicated that in solidly grounded systems, line-to-ground-fault recovery voltages do not vary greatly unless influenced by losses, either in the connected apparatus or in the ground (tower-footing resistance). Since this summary in figure 8 excludes the effects of these factors, the crest recovery voltages for any of these cases is probably between 1.5 and 1.75 with 1.65 to 1.7 being typical for higher-voltage systems and 1.55 to 1.6 being typical for lower-voltage systems.

It was of interest to check some of the results shown in figure 8 against calculated results based on injecting the fault current into the network at the fault point and considering the distributed constants of the line. When this was done for several cases, it was found that calculations based on single-circuit traveling-wave theory[3] were in essential agreement.

Figure 9 shows the effect of varying the magnitude of arc voltage in the fault. Over a reasonable range, this factor has little effect on the crest value of recovery voltage for a given case. However, it can be shown that varying this factor does change the fault angle which gives the maximum overshoot.

Figure 10 shows the effect of line grouping on a common bus. This curve shows that for a given aggregate number of miles of line, the time to maximum crest recovery voltage is materially reduced as the line is broken up into more short sections. A minimum value is reached, however, which corresponds to lumping the capacitance of all lines at the point of fault. This fact suggests the possibility of calculating recovery voltages approximately using lumped constants when no long lines are involved.

Figure 11 shows the effect of neutral grounding through resistance. The qualitative effect is very similar to that observed when tower-footing resistance is inserted (see figure 15). This probably is to be expected since the circuit connections differ only slightly for the two conditions.

The effect of reactance grounding is shown in figure 12. Both maximum overshoot and time to crest are significantly altered by this factor. As more reactance is added, time to crest becomes greater because of the lower zero-sequence frequency. This soon becomes the predominant factor in determining both time to crest and maximum overshoot, particularly for the short lines where the effect of the distributed constants of the line become relatively small.

Figure 13 shows the effect of line length and short-circuit amperes when a line is fed from both ends. Qualitatively, the effect is very similar to that shown in figure 8 for lines fed from one end.

The effect of fault location along a line receiving power from both ends is of interest. Figure 14 shows that there is little change in crest recovery voltage, but that there is a significant change in time to maximum crest as the fault point is moved along the line. This effect was much less pronounced for lines fed from only one end. However, a fault at the midpoint of a line fed from both ends in this case is in effect the same as a fault at the far end of two 50-mile lines in parallel and bussed at both ends. Therefore, it appears that the effect shown in figure 10 is playing an important part.

The effect of tower-footing resistance for a line fed at both ends is shown in figure 15 for a single-line-to-ground fault.

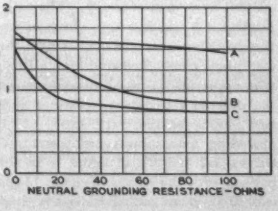


Figure 11. Effect of neutral grounding resistance. One hundred miles of line. X_0/X_1 = 0.4 at source

A—650, *B*—2,200, *C*—4,300 root-mean-square symmetrical line-to-ground fault amperes in 115-kv system for zero neutral resistance

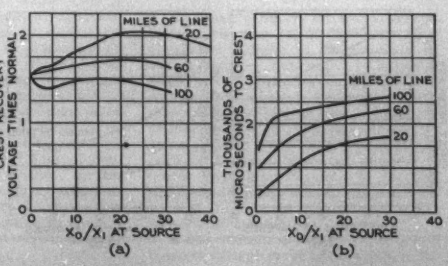


Figure 12. Effect of neutral grounding reactance. Single-line-to-ground fault of 4,300 amperes root-mean-square symmetrical at source in 115-kv system for X_0/X_1 = 0.4

The crest voltage reached is seen to be reduced as the tower footing resistance is increased, and the extent of this effect is greater for the larger available short-circuit currents.

The effect of tower-footing resistance for a line fed at both ends is shown in figure 16 for a double-line-to-ground fault. Three pairs of curves are shown, each set corresponding to certain conditions of fault clearing as indicated.

In the miniature system it was possible to apply the fault simultaneously on phases *A* and *B* at any instant in region 1 of figure 17. In an actual case, double-line-to-ground faults would be quite unlikely to occur in a portion of this region. Present understanding of the behavior of lightning discharges in initiating power-system faults indicates that region 2 of figure 17 would probably be much more susceptible to double-line-to-ground faults since the polarities of the two phases involved are alike while the polarity of the third phase is of opposite sign.[5] Under these conditions, phase *A* will carry only a small minor loop of current prior to the first current zero in that phase. This means that quite likely it will not clear when it tries to interrupt first. Therefore tests made for faults applied in region 2 permitted phase *A* to carry current until the second current zero was reached. The curves marked *A*-2 and *B*-2 were obtained when this procedure was followed. Under these conditions phase *B* cleared first, although with appreciable tower-footing resistance, the difference in time of clearing of the two phases became very small. If the preceding assumptions are correct, the curves *A*-2 and *B*-2 of figure 16 in comparison with the curves of figure 15 indicate that in an actual case, the single-line-to-ground-fault recovery voltage is generally more severe than the corresponding double-line-to-ground recovery voltages where tower-footing resistance plays an important part in determining the minimum values of current to be obtained.

The two curves labelled *A* and *B* are the maximum recovery voltages on phases *A* and *B* respectively obtainable for applying the fault simultaneously at any instant on phases *A* and *B*, and each phase clearing in proper sequence at its first subsequent current zero. Curve *A* shows the highest recovery voltage reached on phase *A* for a fault applied simultaneously on phases *A* and *B* at such an instant that voltage on phase *A* was in the vicinity of maximum. Curve *B* shows the highest recovery voltage reached on phase *B* for a fault applied simultaneously on phases *A* and *B* at such an instant that voltage on phase *B* was in the vicinity of maximum. Phase *B* as defined will be carrying much less current than phase *A* for a practical range of tower-footing resistance, and in fact, may even be carrying less current than would flow for a single-line-to-ground fault. Analysis of figures 15 and 16 indicates that the double-line-to-ground fault under these conditions may be much more difficult to interrupt than the single-line-to-ground fault for certain values of tower-footing resistance.

The preceding analysis indicates that phase *B* (which would tend to clear first) may be difficult to interrupt. Therefore phase *B* was permitted to restrike in the miniature system so that phase *A* would be forced to interrupt first. When this was done, the pair of curves indicated as *A*-1 and *B*-1 were obtained. This made the recovery voltage on phase *A* very high while on phase *B* it had been reduced. The situation had not been entirely relieved since the recovery voltage on phase *A* was so high as to cause possible difficulties of interruption even though it was carrying the greater current.

Therefore it appears that if double-line-to-ground faults could occur at any time, without regard to the relative polarities of the phases involved, the recovery voltages associated with this type of fault would be a very important factor in the selection of protector tubes in many cases. It is quite likely, however, that relative polarities determine the conditions under which a double-line-to-ground fault can occur in an actual system, and for that reason the relatively high recovery voltages which can be obtained in a controlled miniature system are seldom, if ever, obtained in an actual system for this type of fault.

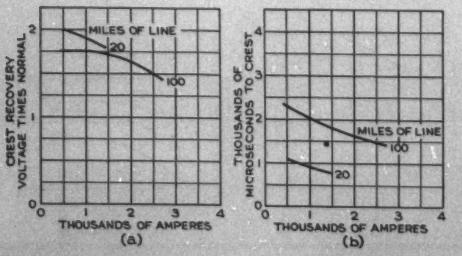


Figure 13. Effect of fault current. Equal generating capacity at both ends of line. Solidly grounded system. Currents are root-mean-square symmetrical amperes for line-to-ground fault at one end in 115-kv system

Appendix. Operation of Recurring-Fault Electronic Switching Circuits

In figure 3, the fault point designates any place in a network at which the recovery voltage following clearing of a fault at that point is desired. This fault is shown occurring to ground, but in the general case, this need not be true. It may be thought of as occurring between any two points in a network, for example, line-to-line in a three-phase system.

The thyratron in figure 3 can be made conducting at any instant by making the grid sufficiently positive, provided the anode of the tube is sufficiently positive to cause striking of an arc. Essentially, this results in a short circuit between the fault point and ground, and in the miniature equivalent system would represent a fault on the actual system By synchronizing an applied positive impulse to the grid of this tube with the system voltage, the fault may be repeatedly applied at any point on the voltage wave. Fault current will flow from the time the fault is applied until the first subsequent current zero when the thyratron will automatically cut off the fault current. The voltage appearing across this tube will correspond to the actual recovery voltage of the system represented.

The thyratron serves to simulate the arc voltage drop of certain devices, such as expulsion tubes, for instance. The amount

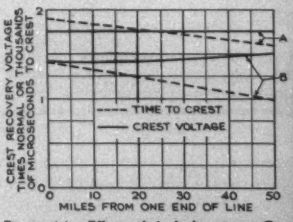

CREST RECOVERY VOLTAGE TIMES NORMAL, OR THOUSANDS OF MICROSECONDS TO CREST
A
B
TIME TO CREST
CREST VOLTAGE
MILES FROM ONE END OF LINE

Figure 14. Effect of fault location. One hundred miles of line with equal generating capacity at both ends. Solidly grounded system

A—1,240 root-mean-square symmetrical line-to-ground fault amperes at either end in 115-kv system

B—2,740 root-mean-square symmetrical line-to-ground fault amperes at either end in 115-kv system

of arc drop is fairly constant for the tube during the time of current flow. The magnitude of arc voltage for specific cases can be varied by inserting a fixed direct voltage (for example, a storage battery) in series with the tube and the over-all drop can be made greater or smaller than the arc voltage of the tube alone.

The purpose of the portion of the circuit on the left-hand side in figure 3 is to time the application and removal of the fault so that the transient condition is repeated in synchronism with the system voltage. The time constant of the series circuit R_1C_1 can be varied to correspond roughly to the time for two, three, or any desired number of cycles of base frequency (preferably not more than about six). If the neon tube is not conducting, the voltage across C_1 rises exponentially with time when the direct voltage is applied. With the transformer unexcited, this same voltage appears across the neon tube. When this voltage reaches a certain value, the neon tube will suddenly become conducting and discharge the capacitor C_1 rapidly through L and R_2, the time constant of this path being small as compared with R_1C_1. The purpose of L is to prolong the duration of this discharge

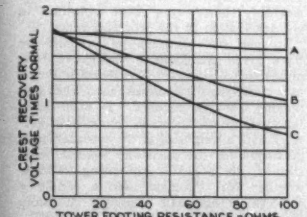


Figure 15. Effect of tower-footing resistance. Equal generating capacity at both ends of line. Solidly grounded system

A—100 miles of line; 414 root-mean-square symmetrical line-to-ground fault amperes at either end in 115-kv system

B—100 miles of line; 1,240 root-mean-square symmetrical line-to-ground fault amperes at either end in 115-kv system

C—20 miles of line; 1,460 root-mean-square symmetrical line-to-ground fault amperes at either end in 115-kv system

so that the thyratron will have ample time to ionize. Immediately after the discharge, the neon tube becomes nonconducting and the cycle repeats itself automatically.

The purpose of the transformer is to add a small alternating component of system or reference voltage. The resultant voltage appearing across the neon tube while it is not conducting is the sum of an exponentially rising voltage and an alternating voltage of reference frequency. Therefore if the time constant R_1C_1 is made such that breakdown voltage of the neon tube is not reached on the second cycle, for instance, but is reached on the third, the frequency of firing the neon tube is made to interlock with the system frequency, and this will be repeated automatically every three cycles.

The frequency of repetition depends essentially on the time constant R_1C_1. If the impulse of voltage appearing across L and R_2 when C_1 is suddenly discharged through the neon tube, is applied to the grid of the thyratron, then the fault condition desired will be repeated in synchronism with system frequency.

The primary of the synchronizing transformer is excited from a phase shifter which is excited from the same source used to energize the miniature system. By rotating the phase shifter, the complete circuit can be made to apply the fault repeatedly at any desired point on the voltage wave. When an oscilloscope is used to view the repeated transient, it can be made to appear stationary on the screen.

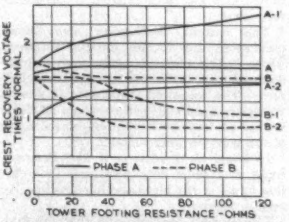


Figure 16. Effect of tower-footing resistance and angle of fault application. Equal generating capacity at both ends of 100-mile line. Double-line-to-ground fault on phases A and B at one end. Solidly grounded system. $I_A = I_B = 1{,}640$ root-mean-square symmetrical amperes in 115-kv system for zero tower-footing resistance. See figure 17 for definitions of regions indicated

A and *B*—Maximum for interruption at first current zero

A-1 and *B*-1—Maximum for phase *A* carrying one loop and phase *B* two loops

A-2 and *B*-2—Maximum for phase *B* carrying one loop and phase *A* two loops

The tendency of a protector tube to interrupt before normal current zero can be simulated by means of inserting a small resistor in series with the faulting device and synchronizing as above a current surge of controlled magnitude and shape through this resistor. Thus a voltage is built up in opposition to the flow of fault current just prior to interruption so that the fault current is forced to zero sooner than it would be if normal conditions continued to exist. This introduces the characteristic rise in arc drop just prior to interruption of current flow and is of significance in some cases, particularly where the natural frequencies are high. Thus the effect of arc voltage characteristics can be simulated in great detail, not only for protector tubes, but for other interrupting devices as well.

The circuit shown in figure 4 is very similar to that of figure 3 in principle. In this case, two thyratrons are fired simultaneously in synchronism with the system frequency, thus making it possible to simulate double-line-to-ground-fault conditions in the miniature system.

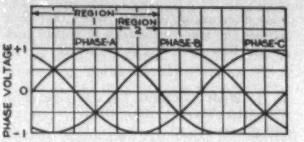


Figure 17. Regions of fault application

The circuit of figure 5 was used in applying double-line-to-ground faults when it was desired to investigate region 2 of figure 17 and permit current to flow in phase *A* until interruption occurred at the second current zero. The first loop of fault current in phase *A* was carried by S_2 and the second loop by the thyratron in parallel with it. Since phase *B* carried only one loop, it was carried entirely by the thyratron. S_1, S_2, and S_3, were all operated by synchronous contactors opening and closing at the proper times to produce the desired switching sequence. The contactors were mounted on an adjustable rack so that the angle of fault application could be varied as desired.

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2. Recovery Voltage Characteristics of Typical Transmission Systems and Relations to Protector-Tube Applications, **R. D. Evans** and **A. C. Monteith**. Electrical Engineering, August 1938, page 433.

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Discussion

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper represents a valuable addition to the literature on voltage recovery transients. It is understood to refer primarily to the behavior of expulsion tubes. It has not yet been shown whether rate of rise of recovery voltage, or time to recovery crest and its value or some other characteristic of the recovery transient limits the capacity of certain interrupting devices. In fact, different interrupting devices may well be sensitive to different elements in the recovery characteristic.

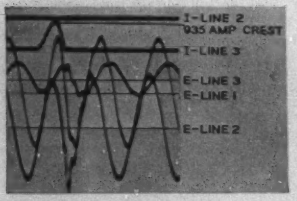
In due course it is hoped that an actual recovery strength curve will be available for

each interrupting device. When that time arrives the true significance of papers such as Mr. Peterson's can be measured.

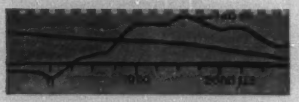
E. J. Wade (General Electric Company, Pittsfield, Mass.): This paper is an excellent contribution to the literature on recovery voltage and Mr. Peterson is to be commended for his exhaustive study of the subject.

Because of the similarity in the results of this paper and that by Evans and Monteith, they mutually support each other although differing in details. This statement has even more significance when it is remembered that the circuit for the line representations and the switching methods were both different.

In almost every respect the agreement, where the results can be compared, is very close but it may be worth while to examine one point of difference which can perhaps be explained. Comparing figure 4 of the Evans-Monteith paper with figure 6 of Mr. Peterson's paper, it will be noted that the first crest of the recovery voltage is much more prominent in the Evans-Monteith paper, and the voltage thereafter drops considerably before increasing again to the second crest. In Mr. Peterson's paper (figure 6) the first crest is less marked and



(a) Magnetic oscillogram (voltages measured at generator bus)



(b) Cathode-ray oscillogram. Voltage on line 3

Figure 1. Single-phase test on 115-kv circuit. Fault at near end of 60-mile line

thereafter the voltage does not drop before being increased by the reflection from the far end of the line. Wave shapes which have been measured during field tests more nearly approximate the curves given in Mr. Peterson's paper and the question arises as to whether this difference in wave shape is due to a difference in the assumed constants, or to the method of representation of the line.

It is of interest that the data represented by figure 6a of Mr. Peterson's paper was obtained with the circuit set up to simulate, as nearly as possible, the conditions found on a field test on the lines of the Boston Edison Company.

The oscillograms for this test are shown in figure 1 of this discussion. In general, the wave shapes, and time to crest, check very closely with Mr. Peterson's results, although there are minor differences in details, which may be attributed to the fact that the 60 miles of line was obtained by looping a 30-mile section of double-circuit line on opposite sides of the same towers. This introduces a small effect due to coupling which was not simulated by the miniature setup.

The current oscillogram also shows oscillations due to the starting transient which in this particular case were entirely damped out before the current reached zero. The measured initial rate of rise of voltage was 190 volts per microsecond which is a satisfactory check of the calculated value of 175 volts per microsecond.

It would be of interest if Mr. Peterson could give some data regarding the relative losses in the high- and low-loss lines as used in figure 6.

I agree with Mr. Peterson that the first crest is not of as much importance as the entire shape of the recovery voltage wave, and because the first crest tends to be obscured in some cases, further agree that it would be preferable to use 90 per cent of the crest of leg voltage as this gives a definite value of voltage at which the corresponding times may be compared.

R. D. Evans, A. C. Monteith, and R. L. Witzke (all of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The subject of switching transients has been under discussion for some years. Due to the complexity of the problem, analytical work has been rather limited, the best conclusions being taken from actual system performance. Recognizing the needs for a method of calculation and for further refinement in theories, the a-c network-calculator method or miniature-system method was developed and presented[1] two years ago at the summer convention in Milwaukee. At that time it was introduced as a method that could be used for analyzing recovery-voltage problems, but it was also recognized that it "opened the way to a systematic general investigation of recovery voltage transients and related problems" and presented "a practical method of determining the electrical transients of systems." A review of the discussions presented indicates that at that time the method was considered radical and skepticism was expressed as to its broad usefulness.

It is encouraging to us to note that several papers presented on this subject today make use of this method. It is our firm belief that this method will receive even broader usage.

The paper by Mr. Peterson is of interest in that it so closely parallels our work, the results of which were presented[2] at the last winter convention. Where comparison can be made the checks are surprisingly close. Any differences appear to be due largely to differences in assumptions rather than to differences resulting from the actual application of the method or from the introduction of refinements.

We do not clearly understand Mr. Peterson's statement as to the difficulty of summarizing the first crests and including the effects of initiating transients. A summary of measurements of first crests was presented in our paper.[2] In that work we made adjustments to include the effect of the initiating transients, the fault being applied so as to make the first crest a maximum. We feel that this is essential as in a large number of cases the design of the protector tube is determined by the first crest.

Quite often, depending upon the system characteristics, the recovery voltage curve may have several crests before maximum is reached. In our paper presented last year,[2] we not only summarized the first crest but also the succeeding significant crest, having in mind the protector-tube application. Mr. Peterson apparently has summarized the maximum crest with its corresponding time. The fact that our paper summarized the "significant crest" and Mr. Peterson's paper the "maximum crest" will account for differences in the data. This is a possible explanation of why Mr. Peterson's summary showed relatively higher voltages for the high-voltage systems. It was our opinion, that the times associated with these higher voltages were so long as to make the slightly lower voltage with a considerably shorter time more important in the application of the protector tubes.

In the representation of systems we have given considerable thought to the networks to be used. We found it necessary to weight the constants used when employing a π-type network. In most cases, however, we used a more complicated network with a weighting of the constants proportioned for the particular system being studied. It would be interesting to know whether Mr. Peterson used a simple π network or one with weighted constants for the short line sections.

Electronic devices for controlling the application and removal of the fault are convenient and advantageous where the electronic tube characteristic closely follows that of the arc path desired for the study. This arc characteristic does not, however, lend itself to broad transient analysis. It is for this reason that, after giving consideration to the use of the electronic device and the synchronously driven switch, we chose the latter, preferring to have one device for general investigation.

In eliminating the consideration of the double line-to-ground condition for the application of protector tubes, Mr. Peterson has considered the zone where the instantaneous voltages on two phases are of the same polarity and of practically equal magnitude. It is our opinion that the power-system voltage is low in comparison with that of lightning and therefore that the effects of polarity and magnitude of the normal system voltage are negligible. Lightning can strike any phase, and cause the breakdown of one tube which in the more severe cases will cause a rise in the potential of the ground point and result in a flashback through one or two of the remaining tubes. If this is correct the double-line-to-ground fault can occur at any point and cannot be eliminated from consideration.

There is an intermediate range of tower resistance that makes it possible for the first tube attempting to clear for the double-

line-to-ground fault to hang on and for the second tube to clear. The condition would then be that of a single-line-to-ground fault and the first tube would then clear. Such operation would subject the first tube to considerable erosion. However, for both the lower and the higher values of resistance, the severity on the two tubes is so closely the same that if one fails to clear, the other will probably not clear. We therefore feel that the recovery voltage conditions for double-line-to-ground should be considered in the selection of the tube.

In conclusion it is of interest to point out that no factor has been uncovered in these investigations to question the grounded-neutral system which is in general use in this country.

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2. RECOVERY VOLTAGE CHARACTERISTICS OF TYPICAL TRANSMISSION SYSTEMS AND RELATION TO PROTECTOR-TUBE APPLICATION, R. D. Evans and A. C. Monteith. ELECTRICAL ENGINEERING, volume 57, August 1938, pages 432–43.

Harold A. Peterson: The interest aroused in the general subject of overvoltages as indicated by discussions both written and oral reflects the importance of being able to obtain readily quantitative results such as those presented in my paper. The miniature-system method of actual system representation appears destined to continue to play an important part in arriving at a better understanding of numerous closely related transient and steady-state phenomena. Since this practical tool for evaluating voltage recovery characteristics for a variety of interrupting devices under various operating conditions has been developed to a stage of usefulness, it is hoped that similar progress can be made in determining the recovery dielectric strength curves for each interrupting device as well, so that the problem of co-ordination between such curves and voltage recovery characteristics can be placed on a sound engineering basis as Mr. Prince suggests.

In comparing figure 6 of my paper with figure 4 of the Evans-Monteith paper (reference 2), Mr. Wade has brought out a significant point. The following discussion will explain the cause of this point of difference in results and will answer several of the questions raised by Messrs. Evans, Monteith, and Witzke in their discussion. The reason for this point of difference can best be understood by considering various methods of representing the transmission line in miniature. Figure 2 of this discussion shows a family of voltage-recovery curves obtained for an assumed actual system. Each curve corresponds to a different method of representing the actual system as indicated. The fault was left on sufficiently long in each case so that interruption took place from a steady-state condition (that is, there were no initiating transients and only symmetrical power current was flowing). It will be observed that the curve *A* obtained using nine π sections for the 90 miles of line closely approximates the behavior of a uniformly distributed constant line (curve *D*). This approximation is very good, even to the timing of the return of the reflected wave from the far end of the line. Since no losses were assumed in calculating curve *D*, it is to be expected that the crest voltage after reflection would be higher than that actually obtained in any of the miniature system setups.

Curve *C* obtained for a weighted-constant double-π representation shows a tendency

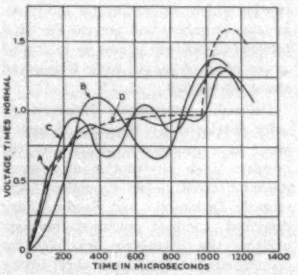

Figure 2

to give a higher first crest voltage than that obtained either with the nine π sections or by distributed-constant calculations. There is a pronounced voltage drop after this first crest is reached before the voltage continues on upward to the maximum crest value. It will be observed also that the axis of oscillation of this first period is the true exponentially rising recovery characteristic.

Curve *B* shows the recovery characteristic for an equivalent double-π representation (not weighted). This gives a still higher first crest voltage, but the axis of oscillation appears to be approximately the exponentially rising true recovery characteristic.

Several points of interest may be noted in this figure. All three methods of miniature representation considered yield essentially the same time to maximum crest voltage, and only slight discrepancies appear to exist for the magnitude of the maximum crest voltage. The greatest discrepancies occur during the initial period before the reflection returns from the far end of the line. The first crest voltage obtained for a double-π representation, weighted or not, characterized by magnitude and a time to that magnitude, *does not lie on the true system recovery characteristic.* With the nine π section representation there are several oscillations, small in magnitude, which deviate only slightly from the true recovery characteristic. It is for this reason the statement was made that it is difficult to summarize the initial part of the recovery characteristics in terms of a first crest and a time to first crest. This analysis may account for the fact that some of the first crest voltages obtained by Messrs. Evans and Monteith[2] appear to be high. First crests, at least in part (depending on initiating transients), are characteristic of the miniature system representation, and in general, may not be characteristic of the actual system it was intended to represent. As indicated by the curves of figure 2, time to 90 per cent normal voltage would have more significance in interpreting results obtained in our miniature system where each artificial π line section represents ten miles of actual line. Experience, as illustrated by these curves, indicates that for lengths of line as short as 20 miles, such π representation does not give very accurate initial recovery conditions. However, maximum crest and time to maximum crest voltage are not in appreciable error.

It is important to point out that the entire recovery voltage characteristic is important, and therefore any attempt to summarize the severity of the initial period by means of a single magnitude and the corresponding time cannot be entirely adequate.

The low-loss line as used in obtaining results in figure 6 of my paper had an R_1/X_1 and R_0/X_1 ratio of 0.10. The high-loss line had an R_1/X_1 ratio of 0.40 and in addition had a high neutral-return resistance of two ohms per mile to damp out quickly the fault-initiating transients.

Electronic devices for controlling and removing the fault in a miniature system are distinctly advantageous. Fault interruption always takes place precisely at a current zero without adjustment. This is true even for very high natural frequencies of the circuit under investigation. High frequencies present an almost insurmountable difficulty to mechanical devices if flexibility of control for recurring transient conditions is desired. In addition, when electronic devices are used, various arc-path characteristics can be simulated as indicated in my paper. This is of importance where it is desired to know the effect of assumed or known arc characteristics of certain interrupting devices. If the miniature-system voltage base is sufficiently high, the normal arc drop in the thyratron tube becomes insignificant. In cases where such conditions do not prevail the arc drop can be reduced to zero as indicated in the appendix.

It was not my intention to eliminate the double-line-to-ground fault from consideration in the application of protector tubes as Messrs. Evans, Monteith, and Witzke infer. The curves shown in figure 16 were simply intended to illustrate the effects of restriking in the case of a double-line-to-ground fault. A double-line-to-ground fault can occur at any instant regardless of polarity, although the region indicated in figure 17 is probably most susceptible. In case restriking does occur for a double-line-to-ground fault, clearing becomes a selective process. The phase to clear first will then be the one which can be most easily cleared. If the tube is not able to clear the easier phase to interrupt of the two, the fault may continue until cleared by braker action. However, in general, it is necessary to consider every possible instant of fault application and interruption at the first current zero in each phase to insure proper protection over a period of time since any restriking results in excessive erosion of the tube walls.

A New High-Capacity Air Breaker

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MEMBER AIEE

Synopsis: Air circuit breakers for lower voltages of simple design are being replaced by improved types, which incorporate specially designed circuit-interrupting devices for the purpose of improving the interrupting efficiency and minimizing the formation of arc flame and gases. A new form of deionizing arc interrupter is described which is equally effective for both d-c and a-c circuits. A new air circuit breaker has been designed to utilize this interrupter in which carbon arcing contacts are replaced by refractory metal, and laminated-brush-type main contacts are replaced by silver-faced solid copper. These improvements have led to greatly increased current-carrying capacity in breakers of a given size and also large increases in interrupting capacity with a minimum of noise and flame, which permits the breakers to be readily mounted in enclosures and cubicles of small physical size.

I. Introduction

INTERRUPTION of low-voltage circuits in air is so easily accomplished by the mere separation of suitable contacts that it has been unnecessary to develop efficient arc-interrupting devices in order to make air breakers workable. The usual breaker construction permits the formation of an unrestricted arc which lengthens due to a self-generated magnetic field until interruption is accomplished, and meanwhile discharges ionized gases in undesirable quantity to the surrounding space. Such simplicity is permissible if adequate mounting space is available for the breaker, and if there is no objection to the thunderous detonation which accompanies the arcing.

Compact metal-clad switchgear, however, has grown up around the conception of adequate circuit breakers which will take care of the gases and other by-products of interruption in the devices themselves without imposing complications on the bus and mounting structure. Standard practice involves air-insulated busses and connections for the most part with conductor insulation only as protection against inadvertent contingencies. The increasing use of air breakers in metal enclosures is, therefore, creating a demand for carefully controlled arc interruption which will confine the arc to deionizing chambers and prevent electrical breakdown between phases or to ground as the result of ionized flame widespread about the breaker.

Deionizing interrupting devices, originally developed by Slepian and associates,[1] have provided a solution to the problem of air interruption in confined space for several classes of breakers,[2] and recently Dickinson,[3] and Sandin,[4] have described compact enclosed breakers utilizing the deionizing principles for opening circuits of moderate short-circuit current. The development of enclosed air breakers which will interrupt currents up to 120,000 amperes root-mean-square and which will have universal application to both d-c and a-c circuits of 750 volts and below, has however necessitated a new form of interrupting device. In addition, the unusual stresses of such high short-circuit currents have made necessary the development of a new breaker itself for the purpose of minimizing contact burning, increasing interrupting speed, decreasing size, and improving mechanical adequacy. Both the interrupting chamber and the breaker are described in this paper.

II. Deionizing Interrupter

Interruption of high short-circuit currents with scant outward display and virtual freedom from external ionized flame requires a confined arc which dissipates the least possible energy. Although the a-c circuit may be opened with a theoretically very small energy dissipation by rapidly deionizing the arc path near a normal current zero,[1] the d-c circuit discharges an amount of energy in the arc somewhat greater than that stored in the circuit electromagnetically when it is interrupted.[5] The d-c energy dissipation and arcing time can be minimized by developing the highest permissible arc drop which will not endanger the circuit insulation immediately upon separating the contacts, and sustaining this value until interruption is complete. The arc drop which is the product of volts per inch and inches length can be achieved either by considerable lengthening of the arc or by the development of a high voltage gradient along its axis. The latter means is preferable first because the necessary arc drop can be developed most quickly by the introduction of deionizing means to increase the voltage gradient, and second because a smaller structure is required if the arc is kept short. The product of arc length and gradient should be kept substantially constant to avoid overvoltages. It is also necessary that the breaker contacts mechanically separate at high speed in order to provide immediately the necessary arc length.

For best interruption of the a-c circuit, the arcing time should also be kept small. On high-voltage circuits it is preferable to permit the arc to continue to a normal current zero, at which point the interruption is completed. On low-voltage circuits, however, it is also practical to interrupt the circuit in a d-c manner by bringing the current to zero with a limited arc voltage. The power loss in the arc may be increased if this is done, but since the arcing time is shortened the energy dissipation with high current and low circuit voltage will not necessarily be increased.

The usual methods of interrupting an arc do not possess all of the characteristics enumerated. Simple lengthening of the arc with a magnetic field does not sufficiently confine it nor limit its length. Furthermore, the volt-time characteristics of magnetically driven arcs do not have the desired shape for d-c interruption. Finally, magnetic-blowout breakers are notoriously noisy.

Interruption by means of gas blast has been very successful in the operation of fuses. Such means are peculiarly difficult to apply to air breakers however, because of the necessity of almost complete restriction about the contacts. Furthermore, gas-blast devices are generally noisy and have a limited life since material is eroded away in forming the necessary gas.

The deionizing arc chamber[2] meets the requirements of a-c interruption very successfully, and is more efficient than other methods in common use. It is not applicable for currents as high as 100,000 amperes, and because of its principle it is not adaptable for the interruption of the higher-voltage d-c circuits.

An arc may be driven into a narrow slot formed by walls of non-gas-forming insulating material, and if sufficient venting is provided for the gases together with sufficient constriction of the arc, considerable arc drop can be developed. Slepian[6]

Paper number 39-34, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 19, 1938; made available for preprinting December 30, 1938.

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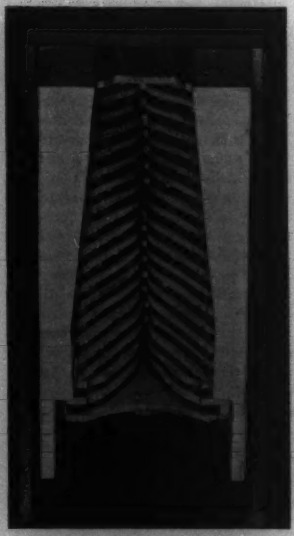
1. For all numbered references, see list at end of paper.

has published data showing that in a one-eighth-inch slot, 800 root-mean-square volts per inch can be interrupted. Deionization chambers made with this principle do, however, fail to limit the arc length and voltage drop, and present problems in venting with very high currents.



(a) Bottom view showing arrangement of insulating plates in arc chamber

(b) Top view showing location of iron plates

Figure 1. Arc chamber

During experiments with arcs in narrowly slotted plates, spaced apart to allow venting, it was found that if the upper part of the slot were closed the magnetic field would drive the arc to the top of the slot, after which the arc core would remain stationary but the field would drive gases turbulently through the arc and deionize it. The construction is similar to one described by Slepian in 1933.[7] In principle the magnetic field acts on the electrons which in turn furnish the gas particles with a resultant velocity by bombardment. Hereby a strong blast of gas is passed through the slots and the arc must, therefore, ionize fresh gas in considerable quantities to maintain a conducting path.

The arrangement finally developed consists of a large number of non-gas-forming insulating plates with V-shaped slots as shown in figure 1. They are spaced with intervals at right angles to the arc path mainly to provide free venting space to the top of the arc chamber for escape of arc gases, thus reducing back pressure which would tend to direct ionized gases downward. It will be noted that the slots are quite narrow at the upper end, while at the lower end they are widened out considerably. This provides room for movement of the arc tips and contact arm. The constriction of the arc in the slots is also important in causing the arc to assume a section which makes the magnetic and gas action most effective.

For convenience, the term "magnetic blast" has been adopted to describe the action, and the device is called a magnetic-blast interrupter.

The magnetic field may be provided by a series coil, but it has been found that an adequate field may be self-induced by building the chamber to contain iron plates as shown in figure 1. With the exception of the actual arc tips it is necessary to keep the arc from striking any metal parts in the arc chamber. Unless this is done the volatile metal resulting from contact with the arc interferes with the deionizing action; and the display of molten metal is objectionable. To obtain this result the iron plates used for intensifying the magnetic field to create the blast are located directly above and in the same plane with the insulating plates so as to be definitely out of the arc path.

The interrupting chamber built in this way limits the arc length to a definite value. During d-c interruption, the field is strongest when the current is high at the beginning of the interruption. Consequently, both the deionizing action produced by the magnetic-blast effect

(a) Closed position

(b) Open position

Figure 2. Circuit-breaker contact construction

of the field and the ionizing action produced by the heavy current in the arc are initially high. As the current decreases, both ionizing and deionizing forces subside and the voltage gradient of the arc remains substantially constant. Since the length is limited and constant when the full value is reached, the arc drop as a function of time approximates the desired curve shape. There is no high overvoltage at the instant of interruption.

During a-c interruption, an early current zero is forced, but the arc drop is not high until the end of the arcing half cycle because of the normally sinusoidal current and its effect on the field. There is only one half-cycle of arcing except when the

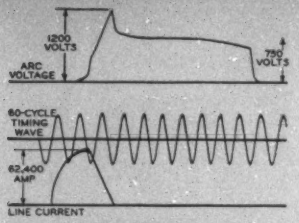


Figure 3. Oscillogram showing interruption of 62,400 amperes at 750 volts direct current

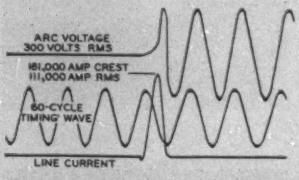


Figure 4. Oscillogram showing single-phase interruption at 111,000 amperes, 300 volts, 60 cycles

contacts part just prior to current zero, in which case the time will be slightly longer.

The arc is well enclosed by the chamber, and the gases which pass between the plates and out the top of the chamber are deionized by the plates so that very little flame passes out of the top. Breakers equipped with these interrupters have been tested in enclosures with the top surface only one inch above the arc chamber, and interruption was satisfactory. The chamber is effective as a muffler, and noise is greatly reduced by its use.

The voltage drop of the arc in the chamber can be as much as 350 vclts per inch direct current, and 550 volts per inch root-mean-square, alternating current. Currents as high as 120,000 amperes root-mean-square have been interrupted satisfactorily.

III. Air Breaker Construction

An air breaker designed to handle considerable current must incorporate a plurality of contact pairs in order to isolate properly the functions of carrying load current and interrupting short-circuit current. If high short-circuit currents are to be interrupted, it is necessary to use three sets of contacts. The first set, or main contacts, serves only to carry load current. In order to make the overall dimensions of an air breaker as small as possible for a given current rating, it is necessary to use materials and constructions for the main contacts which will carry the load currents with as little ohmic loss as possible.

The most satisfactory structure for this purpose has been found to consist of an upper and lower main-contact stud constructed of copper with a solid copper bridging member, which breaks contact when the breaker is opened. The effectiveness of the contacts is greatly increased by the use of silver plates brazed on to the contact faces of both moving and stationary members. The silver should be in the form of a thick plate rather than thin electroplating, in order to provide long life and freedom of maintenance. Sufficient spring pressure must be used to insure a low contact drop with normal load current. It is impractical and unnecessary to utilize spring pressures so high that the main contacts will not be blown apart by heavy short-circuit currents, because in the event of short circuit these contacts must part as the breaker opens; and other parallel contacts must, therefore, be so designed that the main contacts will be well protected.

High-pressure silver line contacts are superior to low-pressure silver surface contacts. As shown in figure 2, the line contact is obtained by machining the face of one silver plate to have the profile of a segment of a circle. Proper alignment of the contacts is necessary to ensure good line contact. This has been achieved by placing the silver at a 45-degree angle on the main contact studs and machining the bridging member so that the contact lines lie on a cylindrical surface. The cylinder will properly align itself with the two planes formed by the stationary stud contact members as the bridge member is somewhat free to slide into proper position.

This main contact construction has proved so effective that the over-all dimensions of the new breaker which will handle 1,600 amperes are no larger than breakers of earlier form, using laminated brush construction, which could carry only 800 amperes with the same temperature rise.

In order to protect the main contacts from being burned as the breaker passes and interrupts heavy short-circuit currents, it is necessary to use a set of protective contacts and a separate set of arcing contacts, as shown in figure 2. The contacts must obviously separate in proper sequence, that is the main contacts part first, then the secondary or protective contacts, and finally the arcing contacts. In order to provide for the proper mechanical sequence of operation it has been usual practice in air-circuit-breaker designs either to make the contact-carrying arm a flexible member or to provide in it a pivoted joint and springs mounted to hold the contacts closed. The flexible-arm construction is not satisfactory since it is too readily bent by magnetic forces associated with extreme short-circuit currents, with the result that the arcing and protective contacts may open before the main contacts. A rigid contact arm, when provided with a separately moving member which carries the arcing contacts and the necessary springs, is difficult to design in a neat manner and also has the disadvantage that its weight and inertia are considerable, which results in a decreased mechanical speed of breaker opening. As shown in figure 2, the necessary relative motion of the secondary and arcing contacts has been provided by a movable platform member on a stationary-contact side of the breaker. As the breaker opens, this platform member moves directly with the contact-supporting arm in such a way that the secondary and arcing contacts do not slide on each other or separate. The necessary freedom for the moving platform member is provided by a slot in the side plates which support it. After a sufficient degree of motion has taken place to separate completely the main contacts, the pin which is a part of the platform member reaches the end of the slot in the side plates and the secondary contacts part. With further breaker

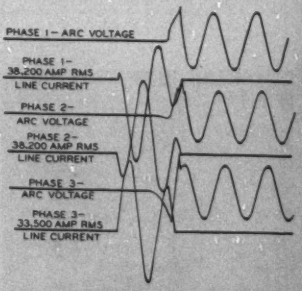

PHASE 1— ARC VOLTAGE
PHASE 1— 38,200 AMP RMS LINE CURRENT
PHASE 2— ARC VOLTAGE
PHASE 2— 38,200 AMP RMS LINE CURRENT
PHASE 3— ARC VOLTAGE
PHASE 3— 33,500 AMP RMS LINE CURRENT

Figure 5. Oscillogram showing interruption of a three-phase short circuit at 600 volts, 60 cycle

motion the platform member pivots about this pin, the secondary contacts on the stationary side move backward, and the arcing contacts remain closed until the stop at the upper portion of the platform member reaches its final position. At this point the arcing contacts separate.

By means of this construction it has been possible completely to enclose the springs and shunts and to provide a simple design unusually neat in appearance.

The secondary-contact material must be chosen to resist some arcing, but at the same time the contact drop must be kept low in order to provide necessary protection for the main contacts. A tungsten alloy has been used. The arcing contacts must be very resistant to damage from the arc, and a similar tungsten containing a higher percentage of tungsten has been used. This material is much superior to carbon since the contacts may be made smaller, more free from breakage, and have better thermal capacity and conductivity.

It is important to use adequate shunts for connection between the secondary and main contacts in order to transfer the current from the main contacts to the secondaries without burning the mains. The shunt, contained within the moving platform member, is inverse in form, so that the heavy short-circuit current will tend to close the secondary contacts tightly together. The current path to the arcing contacts cannot be constructed in this way since the magnetic field must be such as to blow the arc upward from the arcing contacts when it is formed. Consequently, the spring pressure has been made adequate to keep the arcing contacts together under sufficient pressure, even against the effect of very high short-circuit currents.

To protect completely the main contacts from the effect of the arc between the upper contacts, a pair of horizontal overlapping baffles were inserted directly below the secondary contacts. Any gases moving downward are consequently deflected and there is no danger of the arc striking between the mains when interrupting heavy currents.

It is pointed out in section II that high mechanical speed of opening is necessary to minimize the energy which must be dissipated in the interrupter. This has been achieved in the breaker by making the moving contact arm and its associated members as light as possible and by using heavy springs to accelerate the breaker initially. With short-circuit currents in the higher brackets complete operation, which includes tripping of the breaker, mechanical opening, and arc extinction, takes place in a single half cycle. Even in the case of lower short-circuit currents, the operating speed is unusually fast and complete operation does not ordinarily exceed two cycles.

To withstand the forces imposed upon the structure as the result of extreme short-circuit current and the high opening speed, an air dashpot shock absorber was designed to absorb the kinetic energy of the moving-contact arm. Without a device of this kind rebound was noted. The dashpot, however, is so effective that rebound is eliminated. At the same time the stresses are greatly reduced, so that no part is in danger of mechanical breakage.

Figure 6. A complete electrically operated circuit breaker

IV. Interrupting Tests

To obtain the necessary range in current at 600 to 750 volts direct current, test apparatus consisting of four 1,500-kw generators was used. D-c tests were made on single-pole breakers with currents ranging from only a few amperes up to and including 62,000 amperes (table II).

Both single-phase and three-phase short-circuit tests were made at 440 and 600 volts, 60 cycles, using a test set consisting of a three-phase 3,000-kva bank of low reactance transformers. These tests ranged in current values from a few amperes up to 120,000 amperes root-mean-square with crest values over 200,000 amperes. However, in order to obtain currents above 45,000 amperes the low-voltage windings of the transformers were connected in parallel, causing a reduction in voltage to approximately 300 volts. Since all tests above 45,000 amperes were made single phase with 300 volts across the pole, they were equivalent in effect to similar three-phase tests at 520 volts (table I).

Table I. A-C Tests

Test Number	Volts, 60 Cycles	Kind of Test	Actual Current Measured by Oscillograph: Root Mean Square	Crest
Single phase				
1	575	O	4,750	7,900
2	575	O	7,900	11,200
3	575	O	22,300	34,000
4	575	O	32,500	52,000
5	288	O	46,000	72,000
6	288	O	65,000	92,000
7	288	O	76,000	112,500
8	288	O	111,000	161,000
9	288	O	124,000	204,000
Three phase			Phase 1	Phase 2 / Phase 3
10	600	O	34,400	42,200 / 36,600
11	600	O	38,200	38,200 / 33,500
12	600	CO	13,800	14,800 / 17,700
13	600	CO	28,800	30,200 / 24,000

Table II. D-C Tests

Test Number	Volts, 60 Cycles	Kind of Test	Actual Current Measured by Oscillograph
14	750	O	20,000
15	750	O	36,900
16	750	O	62,400

The oscillograms, figures 3, 4, and 5, show how rapidly and smoothly the arc voltage increases and the effective arc-extinguishing action obtained by this means. The arcing time is definitely limited to one-half cycle or less and this coupled with fast breaker action provides an over-all operating time varying from three cycles at low short circuits to one-half cycle at very heavy currents.

The use of the new deionizing interrupting chamber greatly reduces the amount of noise and disturbance which ordinarily takes place when heavy short circuits are opened by air breakers. The ionized flame which ordinarily accompanies interruption was also greatly reduced, and interrupting tests with these breakers in metal cubicles of dimensions very little larger than that of the breaker itself indicated no danger of flashover between phases or to ground.

V. Conclusions

Utilizing the new form of arc-interrupting device in conjunction with an air

circuit breaker improved both electrically and mechanically in fundamental respects, has made it possible to build an air circuit breaker of comparatively small size which will interrupt short-circuit currents up to 120,000 root-mean-square on alternating current, or 62,000 amperes on direct current. The complete breaker electrically operated is shown in figure 6. The noise and demonstration which are usual in air-circuit-breaker practice have been greatly reduced. The ionized flame has also been reduced to an extent that these breakers can be compactly mounted in steel cubicles without the necessity of providing unusual barrier arrangements or dead space above the breaker for taking care of the ionized gases.

Figure 1

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Discussion

Charles P. West (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Messrs. Ludwig and Grissinger have described the latest advance in the circuit-interrupting art. It is another step in the series of breaker improvements founded on Doctor Slepian's fundamental concepts of arc control. The commercial developments arising from these early theories are affecting not only arc-interrupting devices, but the supporting switchboards, structures, housings, and other associated gear as well.

This new breaker design makes it possible to meet the ever increasing demands for reduction in the size of structures. The ability to carry and interrupt current in a given space has been greatly increased. For instance, it is now possible to house three manual three-pole 600-volt 1,600-ampere 60-cycle 40,000-ampere-interrupting-capacity metal-enclosed drawout circuit-breaker units in a space 26 inches wide and 90 inches high. A three-pole drawout unit for 2,000 amperes is shown in figure 1 of this discussion. It requires a width of 30 inches and height of 45 inches. Figure 2 shows the rear of this truck. Note the liberal design of the primary contacts. The safety interlocking features common in metal-clad gear are provided. Three-thousand ampere units are the same width and 60 inches high. Such compactness is now possible because so little clearance over the arc box is necessary and the new breaker frame is much smaller.

Figure 3 shows a structure for 2 600-ampere, 12 1,600-ampere manual, and 4 2,000-ampere electrically operated units. Semiflush instruments and relays for two generators, two transformer banks, a bus tie breaker, and 16 feeders are provided. Two three-phase reactors are mounted in the superstructure. Housing these high-current-capacity drawout breakers in limited spaces requires liberal ventilation. This feature must be carefully watched in the design of the structure and bus compartments. Another factor demanding attention is the locating of the copper for the bus and connecting circuits. As the breaker units get smaller, the width per circuit decreases and it is more difficult to provide accessibility and the required electrical clearances.

Permissible temperature rise in apparatus is basically determined by the top operating temperatures which the materials used can stand continuously without damage. Different classifications are recognized and maximum temperatures determined by the design features of each. As materials and finishes are improved, apparatus can be safely worked at higher temperatures. For instance, bus temperatures are limited so that no trouble will occur in joints. Silver plating eliminates harmful oxides and higher temperatures might well be permitted. Air breakers of the type described by Messrs. Ludwig and Grissinger employ silver-faced solid contacts. Operating temperatures for such a design are less than 30 degrees centigrade and need never be limited to the 20-degrees-centigrade rise often thought desirable for laminated brush breakers. In fact, no serious or permanent damage would result from emergency operation considerably above their rating.

As the performance improves, the size decreases and safety factors are increased, air breakers are finding wider application in fields such as central-station auxiliary service. Here the utmost in reliability is demanded. Low-voltage metal-clad switchgear, as illustrated, provides the safety, interchangeability, reliability, compactness, appearance, and trouble-free operation which are essential to the perfection in design for which central-station engineers are striving.

These various points are discussed to emphasize that, as breaker design progresses, the associated gear keeps pace with it so that the full benefits are made available to industry.

E. A. Childerhose (Jackson and Moreland, Boston, Mass.): The manufacturer is to be congratulated on having taken another successful, even if tardy, step in the development of air circuit breakers. The advantages of air circuit breakers over oil circuit breakers are so numerous that the latter (all voltages) should be obsolete within the next ten years, with the possible exception of special applications in mines and similar locations where the explosion hazard exists and the use of any open arc is prohibitive.

The designers of this new type of breaker have done a commendable job in reducing the space requirements, and have thereby earned the blessings of many a designer, harassed by limited space in which to locate his switchgear. They have incorporated features found in some older breakers, discarded some of the old features, and developed new ones. They have succeeded in developing a snappy, high-speed mechanism that is in many ways superior to the old-style breaker which it supplants. In doing so they have undoubtedly had to compromise between the best and something that is good enough to do the work in order to accomplish the major features desired in the new breaker. These, and the absence of features familiar to the operating man in the old style breakers, naturally raise questions in his mind as to why they were done or omitted. He knew the limitations of the old equipment, and now wants to know what the limiting features of the new will be.

Gone is the familiar brush contact and in its place a silver line contact. Instead of a multitude of small surface contacts is a single line contact. A little bit of arcing

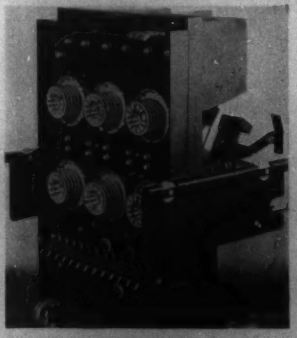


Figure 2

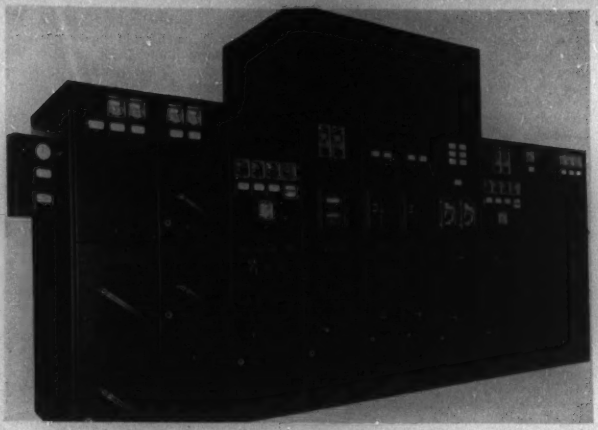


Figure 3

might render a couple leaves of the old brush ineffective, but it reduces the new contact from a line to two points, or possibly even only one! What effect has this on the current-carrying capacity? Will it not be materially reduced, and will there not be an increase in the probability of overheating when the breaker is carrying rated, or even normal operating loads? Silver has a lower melting point than copper and is an excellent solder. There appears to be considerably more danger of a slightly pitted line type of silver contact freezing under moderate overloads, or when opening small-magnitude short circuits, than there is with the brush type of contact.

The spring pressure on the main contacts is not sufficient to prevent them opening under heavy short circuits. The current then travels through the shunt around the bottom contact, and the secondary and arcing contacts. Is the reactance of these shunt circuits sufficiently low to prevent arcing across the main contacts? It is again asked, "What will be the effect of arcing on these silver line contacts?" This is an important consideration when the breaker is adjusted for delayed opening, though because of high operating speeds it may not matter when the breaker is set for instantaneous opening.

The contact pressure of the single line contact has been increased over that used in the brush in order to make it carry rated load. How will it compare when carrying overloads? It is questionable that it has as great an overload capacity.

The authors show oscillograms of the breaker opening 124,000 amperes on an "O" test. How does this compare with the standard "two CO" test for oil circuit breakers? What would the comparative interrupting capacity be? The "two CO" test is such a common reference that many are apt to assume that the currents reported are on that basis, though the authors have made no attempt to intimate such a rating. In what conditions were the contacts after breaking these high currents? Was the breaker operable and capable of carrying rated load after the tests? What was the rating of the breaker tested? Is it to be assumed that all sizes of this new breaker are capable of interrupting this amount of current?

When you buy a car you can test it on the open road and determine the utmost it can produce in speed. When you buy a breaker the manufacturer tells you what the interrupting capacity is, but you are unable to test it for yourself. When you are told that these new breakers can interrupt 124,000 amperes, is that all that they can interrupt, or is there considerable margin of safety in that figure? When you use steel, or wood, or concrete in a structure you know their strength fairly accurately, and can apply safety factors, depending upon the use being made of the material. Why cannot similar information regarding circuit breakers be obtained from the manufacturers, and the purchasing engineer determine the safety factor which should be used for any particular installation?

The paper states that these breakers may be used in cubicles of dimensions very little larger than that of the breaker itself. This brings up the question of temperature rise in such a small confined space. Little is known of this feature to the operating man or to the station designer, and less has been published regarding it. A frank discussion by the manufacturers, and dissemination of their test data on temperature rises in enclosed metal-clad switchboards would be of interest to many. More knowledge of the data used in the recently increased temperature rises permitted by the National Electrical Manufacturers Association would be welcome.

It is acknowledged that silver contacts may be safely operated in excess of 70 degrees centigrade, the limit for copper, but that will increase the ambient temperatures within switch cubicles. Will the higher ambient endanger insulation, will it injure instrument transformers and other equipment which present standards permit being operated at their safe maximum operating temperature in a 40-degree centigrade ambient? It may be that we are not taking full advantage of the possibilities afforded by silver contacts.

This discussion has resolved itself into a series of questions. But they are all questions that a prospective user of new equipment wants answered before he decides to purchase. It is hoped that Messrs. Ludwig and Grissinger will see their way clear to answer them.

The paper brings out another point that is of poignant interest to engineers and the country as a whole, namely, the increasing use of silver in industry. Is it not time that the artificial price of silver were abolished and the metal allowed to assume its true position in industry and the life of the country?

J. W. Seaman (General Electric Company, Philadelphia, Pa.): It is with considerable pleasure that I take this opportunity to commend Messrs. Ludwig and Grissinger on an able presentation of a subject which is of considerable interest, particularly so, to those of us who have been engaged in the pursuit of similar interests for the past several years.

The trend toward metal switchgear has long been recognized by those of us engaged in the art, and I believe I can justifiably say, has been considerably furthered by the work my associates have done during the past several years, although we have not especially publicized the results obtained.

Requirements

To design and build air circuit breakers suitable for metal-clad gear several requirements must be met as borne out by Messrs. Ludwig and Grissinger's presentation.

The first of these is a reduction of size. The use of solid-silver line contacts has been an important factor in accomplishing this, as the authors have pointed out. I should be the last to belittle the undoubted advantages of this construction inasmuch as it has been standard in our designs for some *eight years*. The use of silver alloys for arcing tips is another step in this direction and is now, I believe, quite well recognized.

We engineers would be remiss in our duties if we allowed the reduction in physical size, gained largely by the adoption of a solid-silver contact construction, to be penalized by using (for interrupting means) the conventional plain-break construction. Such means, as we know, demand a prohibitive air space over the contacts when enclosed, in order not to impair the current-rupturing ability.

The necessity for some suitable arc-controlling means has, therefore, long been recognized. If such means is properly engineered, it will (as we have demonstrated through several years of practical application) provide other advantages far greater than the mere saving of space.

Interrupters

Messrs. Ludwig and Grissinger have described a particular arc-controlling means. Happily, as borne out by their presentation, the field in this direction is not particularly limited. There are other equally advantageous means. The one with which I am most familiar is known as the pin-type arc quencher.

The type of interrupter described by Messrs. Ludwig and Grissinger functions it seems, due to what we may call a resistance

characteristic, that is, the arc resistance is increased as a result of decreasing the diameter of the arc core as it travels into the V-shaped slots. To obtain successful operation, Messrs. Ludwig and Grissinger have recognized the necessity of obtaining venting in order to reduce the possibility of developing back pressure sufficient to keep the arc from entering the slots. If the arc is not allowed to enter the restricted slots, this device would apparently become totally ineffective. Apparently the size of the enclosing housing may, therefore, have an important effect upon the performance of this device. The magnetic-blast theory attributed to this interrupter we will leave in the capable hands of Messrs. Ludwig and Grissinger. I believe it sufficient to say that the evidence presented indicates successful operation within the apparent limits of the testing facilities.

The arc-controlling means with which I am particularly familiar is an arc-chute structure comprising a multiplicity of pins through which the arc is driven by magnetic means. This device functions due to the efficient presentation of the arc to large cooling surfaces in combination with a multiplicity of cathode drops. That it has no particular voltage or current limitations has been demonstrated by numerous tests. The arcing time averages less than one-half cycle over current ranges up to and including 125,000 root-mean-square amperes at 600 volts, both single phase and three phase. Due to its freedom from restriction troubles it has been successfully applied over the entire range of air-circuit-breaker sizes during the past three years.

With these test data and operating experience available, we are naturally gratified to find that Messrs. Ludwig and Grissinger concur with us in recognizing the necessity for suitable arc-controlling means, to greatly reduce the usual disturbance associated with the opening of arcs in air, and permit retaining the space advantages already gained by the improvements in contact structure construction.

There is another phase involved in satisfactorily meeting this trend toward metal-clad gear with modern air circuit breakers. This is perhaps not as well appreciated as the phases we have just been discussing but is rapidly assuming greater importance. The increasing demand for electrically operated devices reveals that most present-day air circuit breakers require considerable additional space in order to obtain electrical operation. In the line of air circuit breakers with which I am most familiar, this problem is being met by designs which inherently require only the same small space for electrical as for hand operation. The reception accorded these new breakers clearly indicates that this last trend is not to be lightly ignored.

In concluding, let me again congratulate Messrs. Ludwig and Grissinger on the introduction of their new breaker. With the awakening of new interest even greater improvements in the art, I am sure can be made in the future.

G. G. Grissinger: Mr. Seaman, in his discussion, indicates that the size of the enclosure may have an important effect on the interrupting performance of this device. Recognizing that a limitation of this sort might exist, very thorough tests were made using an experimental enclosure having an adjustable top which could be raised or lowered so as to vary the distance between the top of the breaker and the top of the enclosure. These tests proved conclusively that breakers of this type may be very closely confined without impairing their interrupting ability, since with the top of the enclosure only one inch above the top of the breaker, three-phase short circuits both "O" and "CO" as high as 97,000 amperes root-mean-square were interrupted satisfactorily.

Mr. Childerhose submits a number of very interesting comments. Most of the questions raised can be answered best by reference to test results.

Theoretically, it would appear that a laminated copper brush with its multitude of point contacts would offer much less resistance to the flow of current and, therefore, be more efficient than a solid butt contact. The solid contact, however, can be made much shorter than a brush and with adequate spring pressure behind them the solid silver faces provide a very effective contact-making means. Although the millivolt drop across the contacts may be slightly higher than that of a corresponding brush at the same current, the gain in reducing the length of the current path more than makes up for the difference. Furthermore, a much more durable silver surface can be applied to the faces of solid contacts.

Mr. Childerhose raises a question concerning the effectiveness of the solid contacts after a heavy or a moderate current interruption. Practically no pitting of the silver contacts occurs except when interrupting very heavy short-circuit currents. Temperature tests on these breakers after a series of interrupting tests ranging from small currents to over 100,000 amperes had been made, showed only a few degrees increased temperature rise, even though the breaker had received no maintenance whatever. Consequently, it is apparent that the slight pitting which takes place when interrupting heavy short-circuit currents has very little effect on the current carrying capacity of the breaker. In no case did "freezing" of the silver contacts occur.

As Mr. Childerhose points out, a number of factors influence the protection received by the main contacts. Among them are spring pressure, resistance and reactance of the shunt circuits, and the conductivity and design of the protective contacts. Consequently, all of these factors were given careful consideration in this development. As a check on the final arrangement chosen, additional short-circuit tests were made in which the circuit breaker was blocked so as to prevent tripping. These are ordinarily referred to as short time or five-second tests. The current after reaching a steady-state condition, measured approximately 42,000 root-mean-square amperes and the breaker on which the test was made was rated at 1,600 amperes. This breaker also carried rated current after these tests, with no maintenance, at a temperature rise only three degrees higher than that previous to the tests.

Due to the relatively low thermal capacity as compared with large rotating machines or transformers, circuit breakers are maximum-rated devices, that is, it is not intended they carry more current than their rating for an appreciable length of time. However, the greater durability of the solid contact at higher temperatures makes it eminently better suited to carrying continued overloads than the laminated copper brush which would be severely damaged by excessive temperatures.

The standard interrupting duty cycle for air breakers, as defined by AIEE Standards No. 20, comprises an "O" followed at a two-minute interval by a "CO" test. The 124,000-ampere test referred to by Mr. Childerhose was made on a 3,000-ampere a-c breaker and was an "O" test only. However, many tests have been made both "O" and "CO," particularly on the smaller frame sizes and while the short-circuit currents on these did not exceed 97,000 amperes, three phase, this value nevertheless represents a considerable factor of safety over NEMA standards, which specify 40,000 amperes for a 1,600-ampere breaker and 60,000 amperes for a 2,000-ampere breaker.

In all cases, after completion of the tests, the breakers were in condition to carry rated current without maintenance, although of course the temperature rises were two or three degrees higher than that of a new breaker.

High-Power "De-ion" Air Circuit Breaker for Central-Station Service

R. C. DICKINSON
ASSOCIATE AIEE

Synopsis: The "De-ion" principle of arc interruption in air has been applied over a wide range of a-c services. Difficult switching problems have been met by them. A new breaker has been developed and tested in excess of 37,000 amperes for the 15-kv powerhouse class. It may be supplied for masonry or steel-cell mounting or as part of complete metal-clad switching equipment.

DE-ION air circuit breakers have met some outstanding problems in moderate-voltage switchgear in the past eight years. Since this type gives highly satisfactory operation under severe duty conditions without oil, water, compressed air, or other arc-extinguishing fluid, it is only natural that pressure has been brought by leading users for the extension of this line in the powerhouse field. The purpose of this paper is to describe an important addition to the line tested in excess of 37,000 amperes for the 15-kv class and providing continuous carrying capacities up to 4,000 amperes.

To recapitulate some important services now being performed by De-ion air circuit breakers:

They are giving consistently reliable protection against short circuits up to 500,000 kva at voltages from 12,000 to 16,500, in well-distributed locations throughout the country.

They are handling with a minimum of maintenance, reversing motor service in steel mills in which annual individual breaker operations in excess of 50,000 have been recorded.

Equipped with a special high-speed tripping arrangement, they are opening difficult short circuits on rectifier installations at 12 kv with an over-all breaker time of approximately three cycles (60-cycle wave) and have eliminated potential breakdown such as occurred previously under less effective protection.

In one application they are installed against short-circuit capacities of 1,500,000 kva at 24,000 volts, and giving satisfactory service.

Paper number 39-35, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 25, 1938; made available for preprinting December 29, 1938.

R. C. Dickinson is circuit-breaker engineer with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

In another installation they are handling satisfactorily contact line circuits in 11,000 volt, 25-cycle, single-phase railway service in which short circuits up to 50,000 amperes are possible and these faults are cleared from the system in less than one cycle.

In view of the gratifying performance of breakers of this type in 15-kv powerhouse service up to 500,000 kva, as exemplified in the hundreds of units in use, a large number of which have been in service for several years, development directed toward extension of the fundamental principles to higher interrupting ratings for powerhouse duty followed as a logical sequence. Such extension involved a new conception of contact arrangement not only to provide the higher

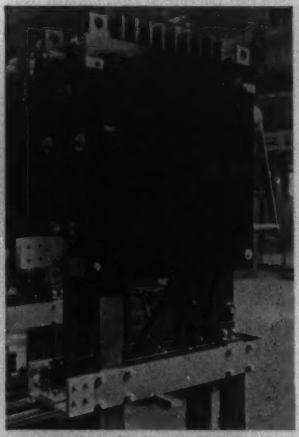


Figure 1. Pole unit of new De-ion air circuit breaker for generation-station service

continuous-current capacity, but to incorporate as well the ability to close in air upon fault currents up to 100,000 amperes crest, to carry these currents until called upon by relay action to interrupt and, finally, to transfer the heavy currents involved to the deionizing chamber without damage to the main or auxiliary contact members. Development into new ground to obtain higher interrupting capacity was necessary, involving means for moving the arc promptly from the contacts to the deionizing chamber, introducing voltage into the arc in steadily increasing steps and assuring speedy, positive interruption. The results of this development are incorporated in a design, set forth in this paper, capable of greater interrupting duty than any circuit breaker available today not requiring liquid dielectric or other form of stored interrupting medium.

Description

Figure 1 shows a completely assembled pole unit with a continuous current rating of 2,000 amperes, placed in service last year. Three thousand-ampere breakers are now being installed and a 4,000-ampere design is available for applications that may require it. All of these current ratings have the same general form except for the current-carrying members. General features of the breaker follow closely the vertical arrangement of elements proved successful by several years' experience with smaller breakers. Mounted on insulated posts of high mechanical strength, the contact linkage is operated from below through an insulating rod pushing upward to close the contacts, with the deionizing chamber mounted at the top of the structure immediately above the parting contact surfaces. The particular structure shown permits a wide range of line connections. Inherently, the breaker is adapted to rear connection, entering either horizontally or vertically, but an additional terminal is supplied to permit one vertical front connection in place of either of the other two. All terminals are arranged for standard bus-bar connections.

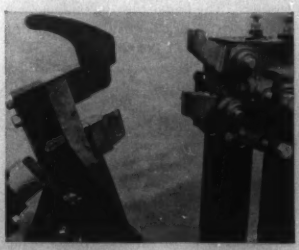


Figure 2. Finger contacts are a radical departure from conventional air-circuit-breaker design. Peak currents in excess of 100,000 amperes were closed with this type of contact during "CO" tests

Table I. Single-Pole Interrupting Tests With Separate Closing Breaker, 15-Kv De-ion Air Circuit Breaker

Test Number	Root-Mean-Square Amperes Interrupted	Breaker Time	Root-Mean-Square Volts Restored
1	4,600	4.2	12,700
2	20,500	4.0	11,800
3	25,000	3.8	11,700
4	30,000	3.9	11,800
5	30,400	3.9	12,000
6	32,200	4.1	11,800
7	32,200	3.8	11,600
8	34,000	4.1	12,000
9	34,600	3.9	11,600
10	41,500	3.8	12,200

As indicated by figure 2, the contact elements of this breaker depart from previous air-circuit-breaker design to permit extending their function as outlined previously. The finger type of contact here shown carries all the advantage accruing from their use in conventional breakers together with the incorporation of features particularly adapted to air-breaker construction. These contact fingers are arranged in two individual pairs, each with its own entering member. The lower set comprises the main current path while the upper set is designed for arc-drawing purposes. Both pairs of fingers consist essentially of parallel bars so arranged as to permit of ample flexible shunts being extended to the line terminal in a straight line thus avoiding local loops with their accompanying current forces in the current path. The fingers are biased toward each other by heavy compression springs with a definite stop maintaining them at proper separation for entry of the moving member. In addition to the self-adjustment permitted by the flexible shunts, the fingers are in effect pivoted in the contact-supporting casting so as to be further self-aligning within the limits necessary to prevent stubbing of contacts upon closing. The main fingers are wide and rugged with sufficient overlap of the entering member to provide the liberal contact surface necessary for high continuous and momentary current duty. The mechanical and thermal sufficiency of this design was well proved by numerous tests in which the fault currents were as high as 104,000 amperes.

New features are incorporated in the arc-drawing pair of fingers. The parallel conducting bars forming the fingers are of high-strength high-conductivity alloy specially heat-treated and only recently made available in this form. An important feature of this pair of fingers is the shape of their contact surfaces. In the fully closed position these surfaces are such that the current path through them (in an elevational view) is substantially in a straight line with the parallel bars and shunts. The lower portion of this surface is cut away so that as the contacts open, the point of contact moves upward making the last point of contact well above the body of the fingers and introducing a sharp local loop in the current path at the instant of initiating the arc.

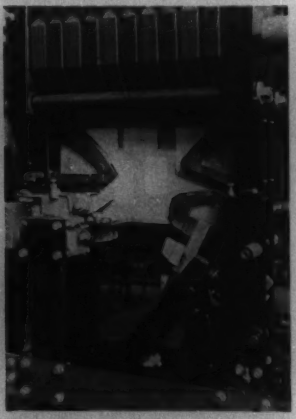


Figure 3. The shape of the arcing contact finger assists in movement of the arc upward to the arc horn without detracting from the ability to close high currents. The arc horns are spaced laminations for free venting and the contour gives rapid motion of the arc terminals

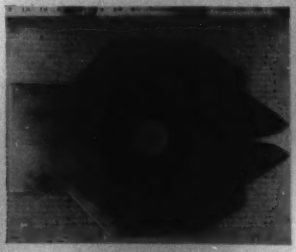


Figure 4. Copper and steel plate combination used in the new breaker

The magnetic force produced by this loop, not present in the fully closed position, assists materially in moving the arc rapidly from its point of origin on the contacts to arcing horns provided for the purpose and reduces to a minimum the burning on the contact surfaces. Both stationary and moving arcing contacts are faced with silver-tungsten, arc-resisting alloy. The moving element, essentially a plate, is formed with a horn to assist the arc in moving upward toward the deionizing chamber, even while the amount of contact separation is still very small. This horn also carries arc-resisting alloy on its upper surface.

This type of contact has several advantages for operation on high currents. Speed of contact separation is an important factor in air-breaker performance. The amount of contact movement afforded by finger-type contacts before actual parting occurs, decreases the accelerating force necessary for a given speed of separation and this decrease in accelerating force also decreases the closing effort, a vital factor in heavy-duty breakers. The finger type of contact also has the property of resisting the tendency to be biased toward the open position under short-circuit conditions which again is reflected in decreased closing effort.

Figure 5. Oscillograms were made of all interrupting tests. The above film shows typical performance at high current values. The short circuit was closed by a separate breaker

The contact-supporting casting is divided into two parts one of which supports both pairs of stationary fingers with their shunts. This contact supporting section may be removed from the main shell of the casting thus permitting maintenance work on the fingers without disassembling other parts of the breaker. As shown by figure 3, a side of the arc box may be removed for a more detailed inspection of this portion of the breaker while the contacts remain in their operating position. It will be noted that the space between the contacts and the lower

end of the deionizing chamber is relatively deep and that the horns provided for arc travel through this space are proportioned to provide a gradual lengthening of the arc, and with it a steadily increasing arc voltage, until it is at the point of entering the slotted plates of the deionizing chamber. These arcing horns are of spaced, laminated construction to provide venting as the arc moves along them.

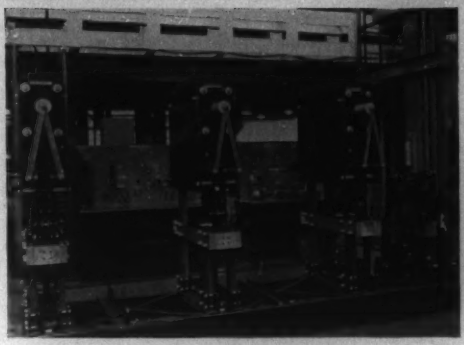
The copper deionizing plates shown in figure 4 are designed from the point of

Figure 6. This film shows the performance of the breaker when closed against a peak current of 96,000 amperes and opened on 34,800 amperes

view of continuing the work done as the arc passed upward along the horns. Extended to the full length of the chamber before entering the plates, the arc first encounters the long, gradually tapered entering slot. Passage along this slot tends to contract the core of the arc ("Extinction of an A-C Arc," J. Slepian, AIEE TRANSACTIONS, volume 48, April 1939), further increasing the arc voltage until at the end of the slot it is ready to transfer to the copper plate surfaces and change from a single long arc to a multiplicity of short arcs in series, each with its own cathode and anode drop. The steel plate surrounding each copper plate, also shown in figure 4, is more liberal in design than in previous structures to provide a stronger magnetic field for moving the arc core along this tapered slot onto the copper plates.

Thermal capacity of the deionizing chamber is a vital factor in interrupting heavy currents with the De-ion air circuit breaker since arc energy is transformed into heat in the process of interruption. Compared with earlier construction, two modifications appear in this design providing increased thermal capacity of the chamber: the thickness of the individual copper plate is increased, and the number of turns in the radial field coils is increased to give a higher speed of arc rotation around the annular path. That is, an increased cubic content of copper per gap provided while the time of exposure of the arc to any particular point on the plate is decreased. Improvement in electrostatic shielding produces more uniform distribution of voltage across the series of gaps to obtain a more efficient interrupter.

Figure 7. Designed to meet particular spacing requirements, this unit illustrates the adaptability of this breaker to meet special conditions



While these breakers are rated at 15 kv they are designed with 23-kv insulation in line with other powerhouse breaker practice. The 54-kv one-minute 60-cycle hold tests, and the 100-kv, $1^1/_2 \times 40$ impulse wave tests were met without unduly increasing the size of the breaker as determined by its interrupting requirements. This applies to all the conventional tests, that is, across the open breaker as well as from the breaker terminals to ground, without the use of any supplementary disconnecting devices.

Three-pole breakers made up of single-pole units here described resemble, in general, earlier constructions of smaller breakers with the three units mounted on a single frame and operated by a conventional solenoid mechanism mounted at one side or underneath the breaker. Figure 7 shows a shaft-operated three-pole breaker with the closing solenoid at one end of a common frame and is representative of general construction in all except pole spacing which was here determined by special installation requirements. This breaker with its $52^1/_2$-inch pole spacing was a complete factory-assembled unit greatly simplifying installation. Figure 8 is a dimensioned drawing illustrating a more compact design with the same pole units spaced $27^1/_2$ inches apart and with the solenoid mechanism located underneath the breaker, operating through a common shaft. This arrangement is well adapted to metal-enclosed construction permitting the mechanism compartment to be completely isolated and accessible while high-voltage parts of the breaker are energized. Figures 9 and 10 illustrate respectively a steel cubicle lay and a horizontal drawout

Table II. Single-Pole Interrupting Tests, 15-Kv De-ion Air Circuit Breaker—"O" and "CO" Operations

Test Number	Peak Current Closed Against	Root-Mean-Square Current Interrupted	Breaker Time	Operation	Root-Mean-Square Voltage Restored
1		4,400	4.4	O	12,600
2	5,600	4,250	4.4	CO	12,600
3		30,300	4.0	O	11,800
4	92,500	31,800	3.8	CO	11,600
5		30,000	4.0	O	11,800
6	96,000	32,100	4.0	CO	11,600
7		35,000	3.9	O	11,800
8	56,500	28,200	4.0	CO	11,600
9		4,600	4.4	O	12,600
10	10,500	5,000	4.6	CO	12,600
11		4,800	4.4	O	12,600
12		34,500	4.0	O	11,800
13	95,000	35,250	4.0	CO	11,600

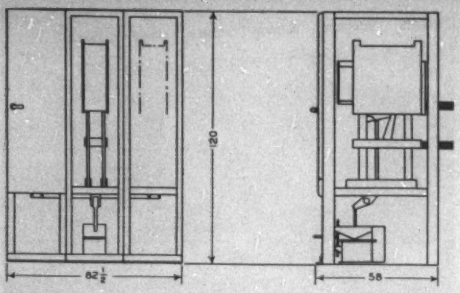


Figure 8. This breaker may be completely enclosed in steel if desired. The result is a comparatively compact assembly

metal-clad unit embodying modern features for this class of equipment.

Tests

In the development of this breaker, the usual insulation tests, operating tests, and current-carrying tests were made. Voltage distribution along the De-ion stack was studied to determine the best type of static shield. And finally, to prove the interrupting ability, several series of tests involving several hundred interruptions, were made, with full generator voltage across a single-pole unit, up to practically the full capacity of the high-power laboratory.

These tests were made on a single-pole unit operated by a conventional four-inch trip-free solenoid having a standard shunt trip magnet. For the sake of simplicity, the first interrupting tests were made without main contacts, the short circuit being initiated by a separate closing breaker. These tests were made with the test generator excited to 13.2 kv, 60 cycles. Figure 5 shows an oscillogram made while this breaker was interrupting 34,000 amperes. Table I shows data taken from typical tests made during this series. Outstanding facts presented by these figures are:

1. The time from energizing of the shunt trip coil to interruption of the circuit is from 3.3 cycles to 4.9 cycles, on a 60-cycle basis for currents from 4,000 amperes upward.

2. The interrupted currents range as high as 41,500 amperes.

3. The restored voltage averages more than 12,000 volts. This is significant in view of the fact that this is impressed on a single-pole single-break unit. Since almost all faults in this type of service involve ground, resulting in considerably less than line voltage being impressed on any one pole, this performance indicates a considerable factor of safety.

Table II shows data taken from a series of 13 single-phase tests made alternatively on the "O" and "CO" basis for customer representatives. These tests were made with the test generator excited to 13.2 kv. Of these tests, seven were at 30,000 amperes or more and the highest current interrupted was 35,250 amperes.

In these tests, the ability to close against high currents was demonstrated. The highest current closed against was 95,000 amperes crest. In other similar tests currents as high as 104,000 amperes crest were successfully closed.

Figure 6 shows a typical oscillogram made on a "CO" unit operation of the breakers.

Tests were then made on the breaker equipped with main contacts, rated at 2,000 amperes, 60 cycles. In these tests the operation was alternatively "O" to "CO." Table III shows results from these tests. The entire series of tests shown were made consecutively and without delay except for precautions to prevent overheating of the deionizing chamber due to the rapid operation at such high currents. By comparison with tables I and II it will be seen that the performance of the breaker under the three conditions is very uniform.

After these tests the breaker was in good operating condition and adequate for further service. The deionizing chamber, though dismantled for inspection, was reassembled and used for additional interrupting tests.

In making the interrupting tests on this breaker, its endurance under severe duty was forcibly demonstrated. In De-ion air-circuit-breaker testing it is quite common to make 20 or more tests without any maintenance on the breaker other than artificial cooling of the deionizing plates, which is required by the rapidity of the tests. For instance in referring to table III, the 21 tests were made in one continuous series. In eight of these tests the interrupted current ranged from 28,400 amperes to 34,800 amperes, six of them being above 30,000 amperes. Of the remaining 13 tests, 7 ranged from 11,800 amperes to 24,800 amperes. The remainder were at currents of from 1,300 amperes to 5,700 amperes. All tests were made with 13.2 kv on the generator. Nine tests were on the "CO" operating cycle and the highest current closed was 96,000 amperes crest. This series of tests was made without any maintenance or parts replacement, except the aforementioned occasional cooling of the deionizing plates. From the users' point of view this performance is impressive, as this one series

Figure 9. Cubicle layout for the new air circuit breaker

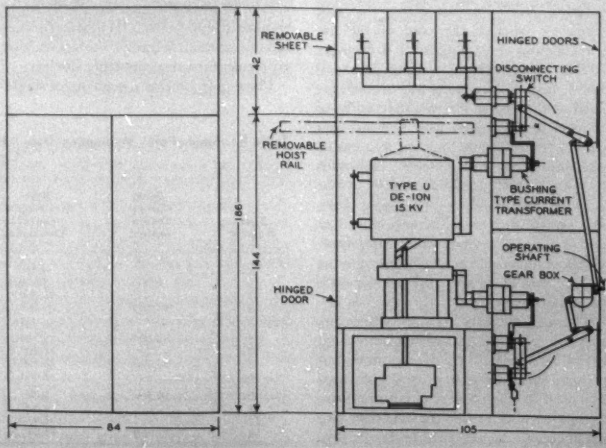


Table III. Single-Pole Interrupting Tests, 15-Kv De-ion Air Circuit Breaker—"O" and "CO" Operations

Test Number	Peak Current Closed Against	Root-Mean-Square Current Interrupted	Breaker Time	Operation	Root-Mean-Square Voltage Restored
1		1,300	5.8	O	12,700
2	2,500	1,400	4.3	CO	12,700
3		3,700	4.6	O	12,700
4	7,000	3,500	4.2	CO	12,700
5		5,700	4.5	O	12,500
6	8,200	4,600	3.6	CO	12,700
7		11,800	4.3	O	12,500
8	27,700	13,300	4.0	CO	12,500
9		13,400	4.3	O	12,700
10		10,200	4.0	O	12,700
11		17,500	4.6	O	11,900
12		24,800	4.0	O	11,900
13	42,500	22,000	4.5	CO	11,900
14		29,000	4.0	O	11,900
15	72,700	31,900	4.1	CO	12,400
16		32,000	4.3	O	11,500
17	49,700	28,400	5.1	CO	11,500
18		32,000	4.3	O	11,500
19	96,000	34,800	4.6	CO	11,600
20		31,300	4.4	O	11,500
21	74,000	31,200	4.3	CO	11,600

of tests is equivalent to many years of service.

Conclusions

Air circuit breakers incorporating fundamental De-ion principles of arc rupture have now been made available to a widening circle of application where, for individual reasons, the air breaker is preferred. Breakers of this type are available for general a-c switching applications at voltages from 2,500 to 15,000, the largest unit in the 15-kv class having been tested beyond 37,000 amperes, with some applications at 24 kv.

The basic De-ion characteristic of a dry breaker has been extended beyond the capacity of any other breaker except those operating in oil or other liquid dielectric. As with earlier forms of De-ion air circuit breakers, this larger breaker lends itself equally well to all forms of modern switchgear construction such as cell, metal enclosed, or truck. It also forms an important element in modernization programs.

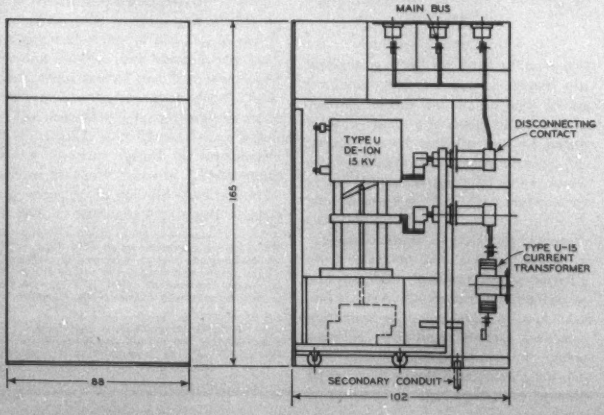


Figure 10. Horizontal drawout metal-clad unit for the De-ion air circuit breaker including well-known features in use with conventional equipment

Discussion

D. C. Prince (General Electric Company, Philadelphia, Pa.): I am sure that the electrical-engineering profession has watched the development of the De-ion breaker with considerable interest since it was first announced at the winter convention of the AIEE in 1929. Since that time added importance has been attached to oilless-circuit-breaker development by a succession of station fires which have not however been attributed to faulty circuit-breaker operation.

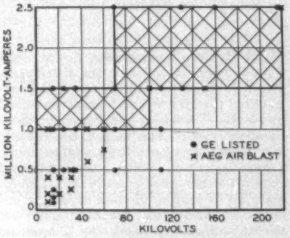


Figure 1. Circuit-breaker ratings

During the same period European manufacturers have been carrying along parallel development of oilless types. There is little doubt that the oil circuit breaker will be superceded by an oilless type if and when such a breaker is developed which offers the service, simplicity, performance, size, and cost of an oil breaker and has in addition no oil. Such a circuit breaker to have an important bearing on switchgear development should satisfy the foregoing criteria over as much of the field as possible.

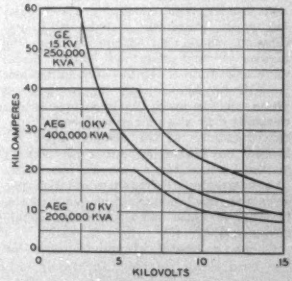


Figure 2. Comparison of interrupting rating in amperes

Figure 1 of this discussion shows the maximum listed rating of standard oil circuit breakers in the United States compared with corresponding ratings in Europe. One is at once struck by the fact that the maximum ratings of European breakers at all voltages are far below those listed and widely used in the United States.

Figure 2 shows the variation in interrupting current at reduced voltage as listed for a standard type of oil circuit breaker compared with corresponding data for European designs. It is again noted that the ability of the foreign designs to handle high currents is far below that of the standard domestic oil circuit breaker.

In the ten years since Mr. Dickinson first described this circuit breaker before this body, maximum interrupting capacity in current seems to have risen from 28,000 amperes to 41,500 amperes and in voltage from 15,000 to 24,000. The oil circuit breaker therefore still occupies the field as the best available means of interrupting all currents and all voltages.

M. H Hobbs (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): It seems to me that one of the outstanding features of the breaker described by Mr. Dickinson is its uniform performance on all currents. This makes the breaker very flexible and permits its application to a wide variety of circuits. One additional application not mentioned in Mr. Dickinson's list is that to circuits supplying arc furnaces, where oil breakers had not proved satisfactory and the operations numbered 75 or more per day. As usual the De-ion breaker is giving a very good account of itself.

Briefly mentioned in the paper were metal-enclosed assemblies incorporating De-ion breakers. The unit is particularly well adapted to cubicles or metal-clad switchgear of the horizontal drawout type. As a matter of fact, if it were not, its value would be much reduced, for modern American practice almost universally requires metal enclosures.

For steel-mill service, requiring more or less frequent disconnecting for safety reasons, and to facilitate the relatively little maintenance required during the regular but short shutdown periods, horizontal drawout metal-clad mounting for the breaker is particularly well suited. Complete separation of the bus and connections from the breaker unit may be provided and phase isolation which this important service demands may also be accomplished. Routine inspection of the contacts after the breaker has been rolled out of the housing becomes a convenient and safe procedure. The same adequate clearances and dielectric strength of insulation which characterize the breaker, are also included in the metal-clad assembly.

Cubicle mounting is more common for powerhouse work involving the heavier breakers and with service which is not so severe as far as repetitive duty is concerned. Isolation of the individual parts of the circuit is no less important, however, and here again the breaker is well adapted to the requirements. To facilitate removal of the arcing chambers, a removable rail is provided, thus giving convenient access to the contacts.

It seems clear that the near future will see the application of this new development to a number of heavier industrial and power-station switchgear installations.

P. H. Adams (Public Service Electric and Gas Company, Newark, N. J.): Mr. Dickinson has presented in his paper a description of the latest development in the air De-ion circuit breaker designed for 15-kv service where interrupting duty does not exceed 800,000 kva. It is to be expected that with further experience and development, the range of this type of circuit breaker will be considerably extended.

Figure 3

In planning the rebuilding of the high-voltage bus at City Dock, one of our important substations, which supplies a low-voltage network, series street lighting, radially fed power, and rectifiers for street-transport service, a great deal of consideration was given to service protection and fire prevention.

Although the circuit breakers already in use in this substation for the high-voltage bus were of a type that contained only 12 or 13 gallons of oil each, they were obsolete and of insufficient rupturing capacity. The interrupting duty required of the circuit breakers in this substation had increased along with the increase in system generating capacity to a point beyond that for which the existing breakers could be rebuilt.

Since new breakers must be provided, it was decided to use oilless circuit breakers. Accordingly, in 1938, eight 1,200-ampere 15-kv De-ion air circuit breakers insulated for 23 kv and to have an interrupting capacity of not less than 750,000 kva, were ordered for use on the 13.2-kv bus.

A heavy steel base of reinforced channel iron construction was provided for each of these circuit breakers so that the operating mechanism and contact elements could be assembled on it and shipped from the factory ready to place on foundations and have the brick cell work built around it. Removable cover plates on the base give access to the operating shaft. A portable rail and trolley hoist can be attached to the top of any compartment to remove the grid element for inspection. The grid element weighs about 1,000 pounds.

Figure 3 of this discussion shows the circuit breaker in the cells with electrical connections ready for service. The cell and base are arranged for a change of the pole elements to 34.5-kv units in the future.

The series of tests given in table II in Mr. Dickinson's paper were witnessed by us in connection with the development of the pole units for the breakers on this order. From the showing made on these tests, it would appear that progress is being made in the development of the oilless type of circuit breaker. It is to be hoped that further developments will bring about the elimination of oil in circuit-opening devices for indoor use in the not-too-distant future.

There is also need for elimination of inflammable fluid in outdoor equipment. The air-blast circuit breaker gives promise in this field and its development for high-voltage service should be continued.

Multiple-Grid Breakers for High-Voltage Service

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Synopsis: There are occasional demands for high-voltage circuit breakers to interrupt in five cycles or less, and to meet this demand, a "De-ion grid" interrupter has been developed which may be used in multiple unit groups for apparatus rated 138 to 230 kv. Records of field tests up to 2,250,000 kva at 220,000 volts are given, showing interrupting times averaging 2.6 cycles (50-cycle frequency). Cathode-ray oscillograms indicate a comparatively small amount of transient overvoltage, less than would be expected from the usual magnetic oscillograph records. With the fast breaker operation, the apparent system voltage dip was small, and freedom from system disturbance and loss of synchronous equipment is noteworthy.

FOR some years the standard breaker interrupting time for high-voltage circuits has been 8 cycles on a 60-cycle basis or 0.133 second.[1] Individual cases have arisen where faster operation has been required, as for instance, the 3-cycle apparatus on the 287-kv Boulder Dam lines.[2] Three-cycle performance at very high voltage introduced special problems and increases the cost of the apparatus involved to a marked degree. On the other hand, it is now feasible through improved interruption methods, to considerably better the 8-cycle standard at a relatively small increase in cost. For the future, therefore, 5-cycle performance on a 60-cycle basis or 0.083 second breaker time from trip coil energization to arc interruption may be procured readily in voltage classes 138 to 230 kv. A multiple-unit De-ion grid assembly to meet these requirements has been developed and tested in the laboratory and the field.

The new interrupter assembly is made of units, each built from a design which has a previous record of satisfactory service at lower voltages. These units are arranged to operate simultaneously to give, at relatively high speed, a series of low-voltage arcs. This arrangement has several advantages: (*a*) each small unit can be tested to the limit of the laboratory power available, (*b*) damage to an individual unit does not impair the operation of the others, and (*c*) mechanical details are readily accessible for inspection and repair. The *CDH* grid after extensive high-power laboratory tests, both in this country and in Europe, was standardized upon two years ago for 46- and 69-kv service. At that time, investigation of voltage-interrupting ability for short grids of this type showed possibilities of its use in the high-voltage field. A small grid designed for 34.5-kv service proved actually able to handle 66-kv circuits and automatically suggested the use of this small unit in multiple assemblies for the high-voltage classes.[3]

Figure 1. Typical three-pole 230-kv oil circuit breaker

Some changes in assembly naturally arose, since at low voltage, the *CDH* grid has been handling heavy currents, and at 220 kv the current-interrupting requirement is in the order of only 6,000 amperes. The finger contact previously used is no longer necessary for conductivity and a simple butt contact not only is adequate in that sense, but provides quicker parting time once the breaker is unlatched. The butt contact also is more economical in space which is particularly desirable when several units are built into a multiple assembly.

The venting of gases from the arc interruption also required consideration. The two vents near the top of the stack which had been found desirable with currents up to 40,000 amperes were retained. The lower part of the stack was entirely closed, except for a rectangular opening in the bottom plate into which the moving contact fits rather closely. This results in sufficient gas pressure within the stack at the lighter currents involved with 220-kv operation, without exceeding a pressure which can be handled safely by the enclosing structure. Each stack is built up of hard fiber plates, tied together with four wood-base Micarta studs. Iron plates are used for directing the arc as in the predecessors of this line of De-ion grid stacks. In general, the assembled unit has much of the appearance of a 34.5-kv stack except that metal top and bottom end plates are employed.

A group of three of these grid units per stationary contact (six per phase) comprises the interrupting element for 220-kv service as shown in figure 2. A similar group of two (four per phase) can be used for 138-kv apparatus, as test results discussed later will indicate. The mechanical linkage at the top of the tank is quite similar to the conventional breaker, except that special high-strength steel is used in places where a saving in mass makes its use justified. Light weight and speed of opening were prime considerations in the design. The usual form of lifting rod and cross bar (figure 3) is used, but the cross bar does not make and break the circuit as in the usual two-break switch. It is used to pick up (in closing) an insulating operating rod to which are attached, through a lever ratio, the three moving contacts of each assembly (figure 3). In opening, the three contacts are moved rapidly under the effect of the butt contact springs and also a substantial spring at the top of the operating rod, the lever ratio making it unnecessary for the lift rod and cross bar to be accelerated at such a high rate.

Considerable effort was put into the design of these fast-moving contact parts as the entire short-circuit interruption takes place within the travel of these small moving contacts and speed consequently is most important. Heat-treated aluminum contacts are used to provide the necessary conductivity and at the same time to secure the greatest speed

Paper number 39-36, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 25, 1938; made available for preprinting December 20, 1938.

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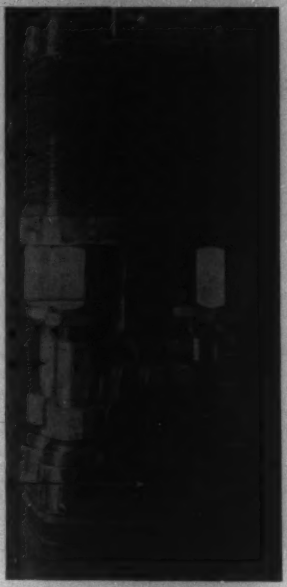
1. For all numbered references, see list at end of paper.

(a)

1—Accelerating spring
2—Dash pot
3—Grid unit
4—Cover plate over stationary contact
5—Operating rod
6—Adjustment
7—Eccentric pin
8—Moving contact



(b)

1—Vents
2—"CDH" grid
3—Moving contact
4—Adjusting jacks
5—Stationary contact spring

Figure 2. Stationary contact assembly for six-grid 230-kv breaker

with least effort, through a reduction in mass. Long life of contacts is assured through the use of tungsten alloy tips to take the burning. The accelerating force of the butt contact springs acts through the first fraction of an inch of contact travel and serves to get the parts into motion as well as providing low-resistance point of contact. Another spring at the upper end of each operating rod acts through the entire stroke and insures that sufficient speed of motion will be maintained until the arc is extinguished. An oil-dashpot effect is incorporated into the upper part of the assembly, bringing the contacts to rest without excessive slam and without rebound. After leaving the interrupting elements of the stationary contact, the cross bar continues to move through a considerable body of clear oil, introducing an oil disconnect into the circuit in addition to the active break of the interrupters.

Alignment of the three grid units of each assembly is secured by adjustable tie rod connectors, providing for correct spacing of the units as well. Fine adjustment of each contact position is easily obtained by turning the eccentric hinge pin (figure 2).

A stationary contact is enclosed within the upper cast end plate associated with each stack. It is hinged at one end, backed up by a substantial contact spring, and protected against excessive burning by means of a face of tungsten alloy, silver soldered in place. For convenience in inspection and maintenance, this contact can easily be removed and replaced together with its spring and flexible shunt, without removing other material, or disturbing adjustments.

Preliminary testing in the high-power laboratory covered a wide range of short-circuit currents and voltages. One series of tests, closing and opening, made with 132 kv impressed across a single pole of a 220-kv breaker, showed uniform duration of arcing from 500 amperes up to 3,000 amperes. Other runs at 88, 66, and 44 kv up to 8,000 amperes gave similar performance, that is, uniform in time up to the highest current interrupted. These results are shown in curves 1–2 of figure 7.

The effect of high kilovolt-amperes per unit was also demonstrated by a series of tests in the laboratory using only two of the six grids. Here again, a very uniform curve of interrupting time against current was obtained up to currents well over 7,000 amperes at 66 kv and 44 kv (see curve 3 of figure 7).

In all these tests, the arc was extinguished within half the stroke of the moving contacts. The oil depreciation was so slight as to be not measurable.

Another series of tests shown in figure 8 was made at approximately 1,000 amperes, at voltages varying from 110,000 to 230,000 volts. All results, when plotted between applied voltage and interrupting time, fell within an envelope not more than 0.02 second wide. This shows the uniformity of operation over a wide voltage range. A similar series also shown in figure 8 with only four of the six grids operating was carried up to 176 kv before

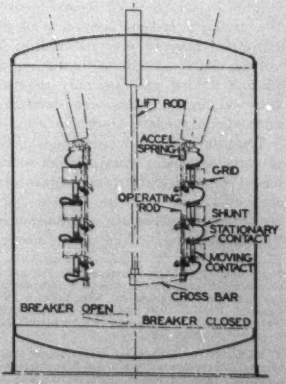


Figure 3. Schematic arrangement of contacts—220-kv, six-grid, in open and closed positions

the breaker failed to interrupt within the grids. The very satisfactory performance on these tests up to well over 132 kv, together with the testing of individual grids to 40,000 amperes at lower voltage, justifies the application of a four-grid assembly to 132-kv high-speed work.

As a result of this laboratory demonstration, arrangements were made for further tests on a three-pole breaker at the Laguna Bell substation of the Southern California Edison Company. This station is centrally located in the system and can produce short circuits of approximately 2,250,000 kva, at an operating voltage of 220,000 volts. A set of contacts, together with the necessary mechanical parts, was sent out from the factory and installed in a type *G-22-A* 187-kv three-pole breaker, which had been in service approximately ten years. Single-phase-to-ground faults were applied, sometimes by the test breaker, and sometimes by a separate closing breaker, to the third pole of the breaker further away from the mechanism. A protective relay operating from overcurrent in the ground lead, tripped the breaker in 0.005 to 0.010 second. A six-element magnetic oscillograph and a cathode-ray oscillograph were used simultaneously to record fault current, voltage across the breaker, relay time, trip coil current, and position of lift rod in one pole of the breaker. Changes in magnitude of fault current were secured by switching lines and transformers at various parts of the system.

Table I. Southern California Edison Company 220-Kv 50-Cycle Tests

Westinghouse Type *G-22A* 187-Kv Oil Circuit Breaker, October 16, 1938

Test	Shot*	Current Interrupted (Amperes)	Equivalent Three-Phase Kilovolt-Amperes	Duration of Short Circuit (Cycles)	Breaker Interrupting Time (Cycles)
1 *W*	O	620	225,000	3.7	3.4
1 *AW*	CO	565	205,000	3.9	3.6
2 *W*	O	1,600	590,000	3.1	2.7
2 *AW*	CO	1,520	553,000	3.0	2.6
3 *W*	O	2,780	1,011,000	3.4	3.0
3 *AW*	CO	2,960	1,135,000	1.5	1.1
4 *W*	O	5,220	1,900,000	3.1	2.6
4 *AW*	CO	5,330	1,938,000	2.5	2.2
5 *W*	O	6,000	2,250,000	3.1	2.6
5 *AW*	CO	6,000	2,250,000	2.6	2.1
GW	Opening 22.9 miles of line—		15 amperes		3.1
MW	Opening 118.1 miles of line—		77 amperes		4.8
BCW	Opening 246.4 miles of line—		150 amperes		5.6

* "O" indicates "opening"; "CO" indicates "closing-opening."

Cathode-ray oscillograms recorded bus voltage to ground on the faulted phase, during the period of arcing, and for a few cycles thereafter. Each record shows a central zero line indicating a closed contact; another trace a small distance away indicating arc voltage, so small as to be scarcely noticeable; and the open-circuit recovery voltage which is sine wave after a short transient generally not exceeding one-half cycle. The maximum peak of recovery voltage obtained on the whole series of tests occurred on the lightest short-circuit values of approximately 200,000 to 225,000 kva. On one of these light short circuits an overvoltage of 170 per cent above normal crest voltage was obtained. For all heavier short circuits, however, the recovery voltage did not exceed 10 or 15 per cent above normal crest. On the lightest short circuits also the rate of rise of recovery voltage was greatest, being approximately 2,300 volts per microsecond. On the heavier short circuits this rate was reduced being approximately 500 volts per microsecond. It is interesting to note that these actual field-test cathode-ray data substantiate calculations made for similar conditions and

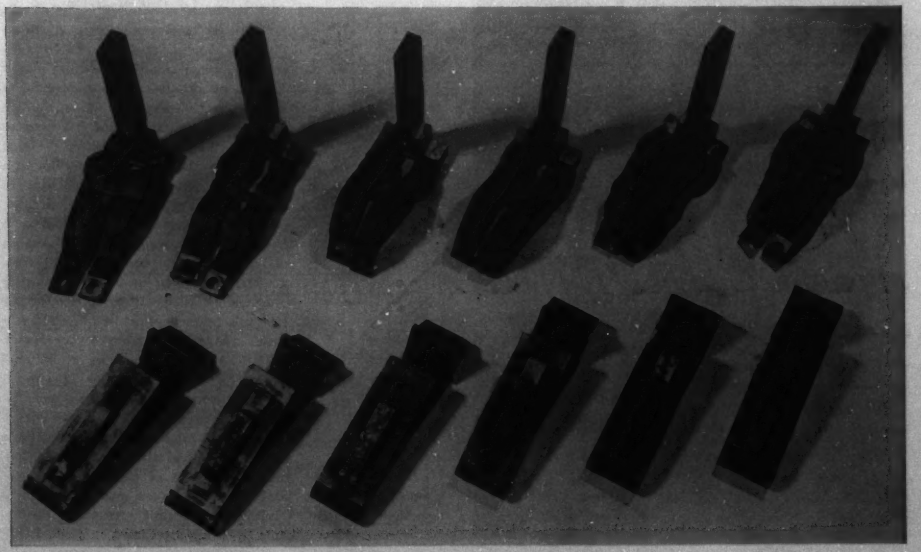
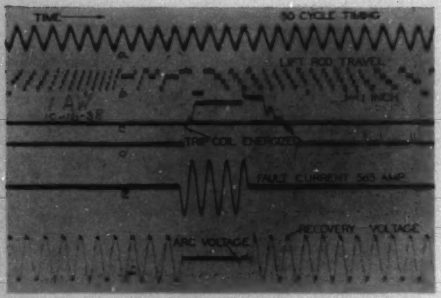


Figure 4. Contacts after field test—ten shots 565 to 6,000 amperes

already presented before the AIEE.[4] Cathode-ray oscillograms of field conditions should be particularly useful in interpreting magnetic oscillograms and Hall recorder films—a more general use of cathode-ray records by operating companies is recommended.

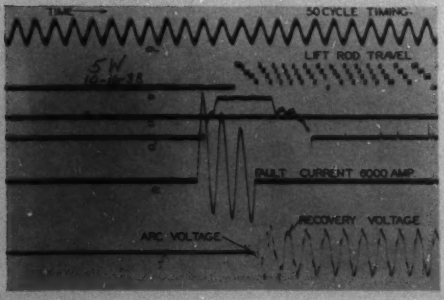
Figure 5. Representative oscillograms (220 kv, 50 cycles)

a—Timing wave
b—Lift rod travel
c—Not used
d—Relay and trip coil current
e—Fault current
f—Line-to-ground voltage



1 *AW*—A CO shot interrupting 565 amperes

3 *AW*—A CO shot interrupting 2,960 amperes



5 *W*—An O shot interrupting 6,000 amperes

Figure 6. Cathode-ray oscillograms—for tests illustrated in figure 5

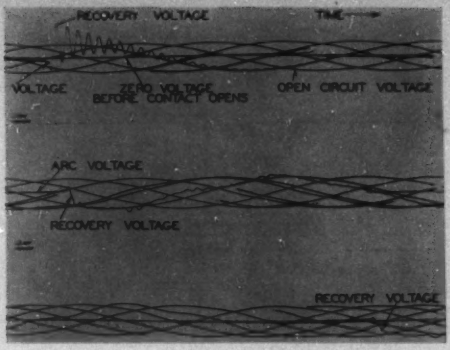


Figure 6 shows three typical cathode-ray oscillograms, with the several parts of each record identified so as to point out the transition from zero voltage before the contacts open, to arc voltage, to the transient at the instant recovery voltage appears and finally, the sine-wave open-circuit voltage. Since the film was rotated on a drum, each trace as it leaves the right-hand end of the oscillogram can be picked up again at the opposite end to form a continuous record.

The results of this series of field tests are shown in the tabulations (table I) and typical magnetic oscillograms are also shown (figure 5). Each oscillogram gives a time record of the position of the breaker contacts (trace *b*) before and after the fault current (trace *e*). The rise of current in the trip coil circuit is shown (trace *d*), lagging the start of fault current by approximately one-third cycle. Movement of the breaker mechanism follows directly thereafter, and arc voltage and recovery voltage (trace *f*) appear as the fault current is extinguished. Voltage records on these magnetic-oscillograph records are somewhat distorted, due to inaccuracies in the measuring circuits, and a more accurate record is obtained from the cathode-ray oscillograph. Values of current and equivalent kilovolt-amperes are given in table I, showing interrupting time averaging 2.6 cycles (50-cycle frequency, or 3.1 on a 60-cycle basis) and ranging from 1.1 cycles at 1,000,000 kva to 3.6 cycles at 200,000 kva.

Importance has been attached recently to the more prompt interruption of charging currents on high-voltage lines than has been practical with old forms of interrupter. As part of the field tests described hereinbefore, a group of charging-current interruptions were made, the results of which are shown in table I, in-

dicating breaker time from energization of trip coil to arc extinction ranging from 3.3 to 5.6 cycles on a 50-cycle basis. The 246-mile stretch of 220-kv line used in these tests is, we understand, the longest 220-kv line on which charging-current interruption has been made under test conditions, the charging current being 150 amperes. Cathode-ray oscillograms of these charging tests show transient voltage phenomena during interruption up to 100 per cent above normal line-to-ground values.

Inspection of contacts showed no excessive burning of metallic parts or fiber plates, nor was there any noticeable oil depreciation. The dip in voltage on the system was so slight as to cause no trouble to connected synchronous apparatus. It is evident that the requirements of five-cycle operation for high-voltage equipment have been met with considerable margin.

Short-circuiting the heart of a 220-kv operating system under load conditions up to three-phase equivalents of 2,250,000 kva involves careful planning and some risk-taking even on a system as robust and well operated as that of the Southern California Edison Company. The difficulties are probably better appreciated by those skilled in system operation under fault conditions than they are by the apparatus designers. However, both have a keen interest in such field tests as they afford the only way of verifying the results obtained in high-power laboratories. We express only the general sentiment of the industry in acknowledging the contribution made to the switchgear art by the Southern California Edison Company in subjecting their system to the tests referred to in this paper.

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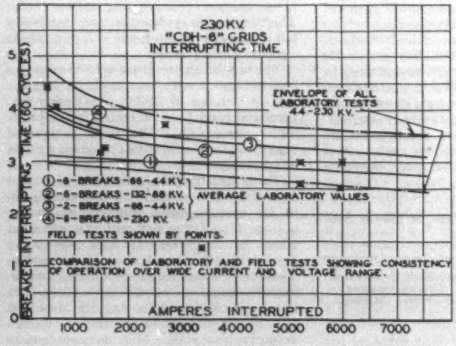


Figure 7. Interrupting performance with varying current

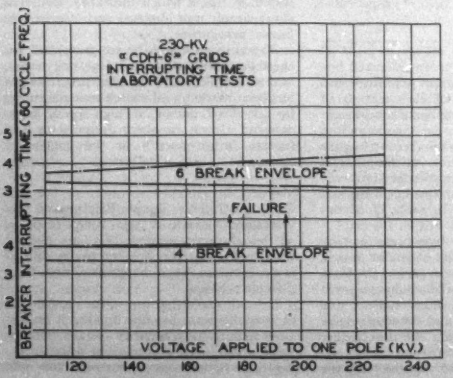


Figure 8. Interrupting performance with varying voltage

Discussion

H. K. Sels (Public Service Electric and Gas Company, Newark, N. J.): Messrs. MacNeill and Hill have presented a very ingenious arrangement of De-ion grid contacts which will speed up and improve the performance of high-voltage breakers. I should like to present some remarks from the point of view of system stability, relay settings, line damage, and breaker rupturing ability using such an arrangement. The arrangement shown decreases the duration of short circuit from around six to eight cycles for the present standard breaker to something less than three cycles. All of these speeds are a great improvement over older types of breakers which have interrupting speeds around 20 to 30 cycles. Naturally there is a great reduction in damage to line conductors and insulators by decreasing the time of interruption to three or eight cycles. However, to obtain fully these benefits with high-speed breakers, it is desirable to use impedance step-type, carrier-current, or pilot-wire high-speed relays to keep the total interruption time as low as possible.

From a system stability standpoint when a system is short-circuited the reactive kilovolt-ampere demand on the system increases enormously and the kilowatt demand on the system may increase slightly or decrease. In any event the distribution of these loads among the generators on the system differs considerably from the load conditions which existed prior to the application of the short circuit to the system. As a consequence certain machines become unloaded and speed up while others tend to slow down. If a short circuit is not removed rapidly enough from the system the phase angles between the advancing and retarded machines will become so great that they will pull out of step. Studies show that great improvement is obtained in removing faults within one-fourth to one-half second but improvement below this point is questionable economically. Unquestionably if we could remove a fault from the system instantaneously we would not have a stability problem but it is doubtful if any such ideal could be approached from an economic standpoint. As a matter of fact we doubt whether there is any advantage of improving speeds below eight cycles.

The rapid removal of a fault from the system and reclosure of the line has been proposed as a means of improving service on our transmission systems. Sufficient experience has not been obtained with this arrangement to warrant such a policy. At this time I doubt very much whether it can be proved economical. In general it seems to me that this field is the only application open to a three-cycle breaker. There are so many improvements available which can be applied to transmission lines generally, such as ground wires, lowering tower-footing resistances, arcing devices, and high-speed relay systems, decreasing the inter-

rupting speed to three cycles is more or less of a refinement for limited application.

Another factor to be considered in extremely high-speed fault interruption is the fact that as soon as you interrupt a fault at less than approximately six cycles the fault current which must be interrupted is asymmetrical and may be considerably above the symmetrical value. This is illustrated in the test oscillograms, figures 5*b* and 5*c*. In other words, within certain limits the faster the fault is removed the greater rupturing capacity it is necessary to provide in the breakers so that while it is advantageous to decrease the time of fault interruption in one respect it is disadvantageous in another. I do not wish to discourage the development of high-speed arc-interrupting devices but do wish to point out those factors which must be considered in their development. The opinions which I have expressed here apply not only to the developments which Messrs. MacNeill and Hill have described but to developments of other designers as well. I believe that if these developments give us a breaker of better interrupting ability it is of a great deal more advantage than the decreased time of arc interruptions obtained. Our sad experiences in the past of the manufacturers derating of breakers, many of which are too recent, emphasize the necessity of improvement along these lines rather than the necessity of further improvement in speed of fault interruption. Of course, if the improved speed in the breaker is inherent with its interrupting ability, that is another story and a welcome one because then we can control the time of arc interruption in relay settings.

D. C. Prince (General Electric Company, Philadelphia, Pa.): The authors are to be congratulated on the high degree of perfection achieved in the development of the De-ion grid. Examination of the successive papers describing the De-ion grid, which have appeared since this device first made its appearance in 1930, shows a steady evolution from the open slots of the earliest designs toward more and more complete enclosure of the arc in an explosion chamber. In the present paper this enclosure seems to be complete and one wonders whether the iron plates in the assembly need be longer retained. If it could be shown that operation is unimpaired by omitting the iron, which is very probable at these low currents, the question might be asked whether there is any distinction between the device of the paper and an explosion chamber.

H. A. Lott (Southern California Edison Company Ltd., Los Angeles): In October 1936, the first of a series of field tests at 220 kv were made on an oil circuit breaker at the Saugus substation of the Southern California Edison Company Ltd. During the ensuing year, 39 single-conductor-to-ground short circuits, varying in value between 0.3 and 1.7 million equivalent three-phase kilovolt-amperes were imposed on the 220-kv system at Saugus and cleared without inconvenience to consumers' service. The number of short circuits at each of the four duties which were used to test three different types of 220-kv breakers are shown in table I of this discussion.

An analysis of the Saugus tests led to the following conclusions:

1. If the over-all time of clearance is in the order of five to eight cycles, similar tests can be carried to the maximum values of 2,250,000 kva without inconvenience to consumers' service.

2. The final proof of a circuit breaker's performance occurs when the breaker is required to interrupt a short circuit at or near its rated capacity. The most practical way to apply such proof is through the medium of staged field tests on a high-capacity transmission system. While both the design and laboratory tests may be carried out with painstaking attention to every detail, such tests, because of limitations in the capacity of the laboratory equipment, fail to disclose occasional weaknesses which are only disclosed when a breaker is tested at or near its rated capacity. Usually such weaknesses are corrected by relatively minor changes in design.

In our discussion on "A New Multibreak Interrupter for Fast-Clearing Oil Circuit Breakers," AIEE TRANSACTIONS, December 1938, the procedure for conducting a short-circuit test at Saugus was outlined, together with some comments on the need for high-speed switching and the experience with high-speed switching on the Southern California Edison transmission system.

The operating results of the Saugus tests were so satisfactory and the interest was so keen that there was no hesitation in staging the next series of tests at Laguna Bell substation. Laguna Bell is at the load center of the 220-kv system, and the 2,250,000-kva duty is the greatest concentration of power at 220-kv available at any location.

The procedure used to conduct a short-circuit test at Laguna Bell was practically identical with the procedure used at Saugus. At Laguna Bell five different line and bus switching combinations were used to obtain five values of short-circuit current. However, since each test presents certain minor variations, a complete analysis was made, and a printed program outlining

Table I. Short-Circuit Tests at Saugus Substation

Number of Short Circuits	Equivalent Three-Phase Kilovolt-Amperes Interrupted (Millions)
8	0.3
6	0.5
6	1.0
19	1.7
39	

each step in the operating procedure was distributed in advance of each test to all station operators and engineers concerned.

During 1938 field tests were made on four different types of 220-kv breakers at Laguna Bell up to the maximum available duty of 2,250,000 kva. The number of short circuits cleared for each of the five values of fault current are given in table II of this discussion.

In one test, three interrupters, each slightly different from the others in design, were installed, one design in each of the three separate tanks of the breaker, and were tested the same day. All three tanks were tested at the same duty and the results were compared before imposing the next higher value of short-circuit current. One design proved superior, and was the only one tested at the maximum value of 2,500,000 kva.

The system performance while the maximum duties were being cleared at Laguna Bell confirmed in every detail the conclusions derived from the Saugus tests. There were no dips in the system speed and no consumer complaints when the short circuits were cleared in eight cycles or less. In a few cases the over-all clearance time exceeded eight cycles. When the clearance

Table II. Short Circuit Tests at Laguna Bell Substation

Number of Short Circuits	Equivalent Three-Phase Kilovolt-Amperes Interrupted (Millions)
22	1/4
16	1/2
18	1
13	1 1/4
8	2 1/4
77	

time was more than eight cycles, the short circuits of both the 1,750,000- and 2,250,000-kva values caused sufficient voltage dip to drop some motors which were equipped with instantaneous undervoltage release coils. There were no indications of instability following any one of the 77 test short circuits.

The test on the multiple-grid breaker for high-voltage service was made at Laguna Bell on October 16, 1938. The design features and results are presented in the paper under discussion. The tests progressed rapidly and as outlined in a program written in advance.

The results from the standpoint of system operation were excellent. There was no dip in the system speed, and the maximum voltage dip of five per cent was recorded when the 2,250,000-kva fault was being cleared in an over-all time of 3.1 cycles. There were no consumer complaints and no inconveniences to service since the short circuits were cleared too rapidly to permit the operation of instantaneous undervoltage release coils. Most consumers were not aware that tests were in progress as the flicker of lights which indicated when the short circuit was imposed and cleared was barely perceptible.

The authors are to be congratulated for their presentation of an interesting paper, and we are pleased to note the progress that has been made by all switch manufacturers in the development of high-speed, high-capacity circuit breakers designed to add further improvements to the continuity and quality of electrical service.

F. W. Gay (Public Service Electric and Gas Company, Newark, N. J.): Where breakers of this type are needed, they are needed very badly and the breaker under discussion seems to be a happy solution to a difficult problem.

It is suggested that one of the most necessary applications for this breaker is on circuits having high capacity, as for instance 132-kv cables. If a breaker of slow rupturing time is used on cables, restriking will

occur. It is believed that multiple breaks, combined with high speed, will greatly reduce restriking.

The advantages of a super-high-speed breaker for ordinary duty have been greatly exaggerated. It is believed that there are a comparatively small number of applications where there is any great advantage from a stability standpoint in clearing a faulted circuit in much less than 20 cycles. If the total clearing time is much under 15 cycles, the rupturing occurs on the subtransient portion of the decrement curve and the current that must be ruptured increases rapidly when times of clearing are much less than ten cycles. If the current to be ruptured is increased, say ten per cent, by shortening the time of clearing the circuit, then the rupturing capacity of the breaker must be increased approximately ten per cent. If no credit is to be given the breaker because of less destruction at the point of fault, due to this shorter time of clearing, and if the high speed is not required for stability, then a fast-clearing breaker of given rupturing capacity must sell for less money than the standard eight-cycle breaker.

Every company should have swing curves for faults on various parts of the system. It is believed that when these swing curves are examined it will be found that there are very few locations, barring generating stations far from their load, where loss of stability or scrambling will occur in much less than three-quarters of a second for a double-line-to-ground fault. Certainly in this case a 20-cycle clearing time is short enough from a stability standpoint.

Better and faster relaying offers a more promising field for development.

W. A. Lewis (Cornell University, Ithaca, N. Y.): The discussion this afternoon has been primarily a description of the mechanical details of the new breaker design, and the performance of these circuit breakers under test conditions. It is interesting to consider the benefits offered to utility system operating engineers by the improvements in the circuit breakers. A large number of tests have been made by the Southern California Edison Company on circuit breakers of various designs. In some of the previous tests, existing breakers having a considerably longer operating time were used in the test. It was found that when the total time of fault clearing exceeded 12 or 14 cycles, a short circuit could be felt by customers on the system, and some motors having instantaneous undervoltage release devices would be disconnected. On the other hand, in tests involving faster operation no trouble at all was experienced by any of the customers on the system. In considering these tests, it should be remembered that all of the faults were single line to ground, and it can readily be seen that for the more severe faults, such as two line to ground, the high speed of operation is essential to avoid customer disturbance when the fault is at a location producing the maximum reduction in voltage. Computations on this and similar systems have, of course, shown that such speeds of fault clearing are necessary in order to maintain system stability. On systems having a large percentage of hydroelectric generation and long transmission distances, rapid fault isolation is much more essential than it is for those systems having all generation by steam, and with shorter transmission distances. However, as system interconnections are increased, rapid fault isolation will become more important even on those systems generating entirely by steam.

Another feature of the paper which is of considerable interest is the fact that the recovery voltage rates indicated by the cathode-ray oscillograms agree fairly well with the calculated recovery rates. A great deal has been done on developing methods of calculation, particularly those using the a-c network calculator, but there are relatively few instances where a direct comparison between calculation and test have been made. It is gratifying to note the satisfactory agreement contained in this case.

The third feature of interest to utility engineers is the fact that these new interrupting devices can be satisfactorily applied to many existing circuit-breaker designs, so that when the improvement in speed of fault clearing becomes necessary, it can be obtained without complete replacement of existing circuit breakers.

W. F. Skeats (General Electric Company, Philadelphia, Pa.): The reference to agreement of the test cathode-ray data with calculations presented in the paper by Messrs. Evans, Monteith, and Witzke is somewhat puzzling in view of the fact that the cathode-ray oscillograms presented in this paper are for short-circuit interruptions, whereas the calculations of Messrs. Evans, Monteith, and Witzke apply to the disconnection of an open line.

It is true in general, as has been pointed out many times in the literature, that an increase in the number of transmission lines connected to a bus tends both to increase the current available and to decrease the recovery voltage rate, so that there does tend to be in many cases a reduction of recovery rate associated with an increase in short-circuit current. Nevertheless, the tests made at the Philo plant of the American Gas and Electric Company as early as 1930 indicate that it is still possible to get high recovery rates with high values of short-circuit current. It would be interesting to know how the device described by Messrs. MacNeill and Hill would perform under such circumstances.

R. C. Van Sickle (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): As an associate of Messrs. MacNeill and Hill, I have had the opportunity of studying in detail the cathode-ray oscillograms of the charging-current interruptions referred to in their paper. Such oscillograms are of considerable interest in showing the voltage existing during switching transients and I wish to call them to your attention.

Figure 1 of this discussion is one of the oscillograms taken during the disconnection of 246 miles of 220-kv line. This is the highest-capacity test of this type ever made. The original oscillogram is about 18 inches long and was made on a rotating drum by a single element recording the voltage to ground of the line being disconnected. The oscillograph was connected to the line close to the circuit breaker.

Figure 1

The sine waves show the normal system line-to-ground voltage and the zero line is located midway between crests.

The trace starts at *A* and moves to the right edge *B*, reappearing at the corresponding point *C* at the left edge. The first clearing occurs at *D*, probably with a very small contact separation since the arc restrikes after a very short interval. The trace goes off the film at *E* and reappears at the left. After a brief interruption, the arc restrikes at *F*. Both of these early interruptions are of such short duration that they do not appear as current interruptions on the magnetic oscillograph film and cause no appreciable voltage transient.

At the next crest of voltage the circuit is interrupted for about a tenth of a cycle. The transient following the restrike at *G* reaches at *H* a voltage which equals 130 per cent of the normal crest of line-to-ground voltage. The trace reappears at *I* and a restrike occurs at *J*. The following crest *K* reaches a value of 180 per cent. After the restrike *L* the maximum voltage obtained on the test, 250 per cent, is reached at *M*. The arc restrikes at *N* and the voltage reaches 215 per cent at *O*. The last restrike *P* produces a voltage of 210 per cent at *Q* and the transient dies out in an oscillation *R* leaving the line charged to about 60 per cent of the normal crest value.

The interruption was accomplished with two interruptions of negligible duration and five which were followed by restrikes which caused overvoltages. The overvoltages reached 120, 180, 250, 215, and 210 per cent of the normal crest of line-to-ground value on successive restrikes and caused no trouble on the system.

H. P. St. Clair (American Gas and Electric Service Corporation, New York, N. Y.): I should like to bring out briefly three or four points in connection with the paper by Messrs. MacNeill and Hill describing a new multiple-grid oil circuit breaker for high-voltage service.

While you are all aware that there has been an increasing interest displayed in this country in the development of oil-blast circuit breakers along lines which are a modification of European practice, at the same time the paper you have heard today, coupled with papers describing somewhat parallel developments presented in the last summer convention of the AIEE, gives evidence of the ingenuity of our American engineers in making notable advances in oil circuit breakers along conventional lines. Fortunately, in this country we are free from most of the restrictions—economic, military, or otherwise—which have forced European practice to a large extent away from oil, so that we are able to go ahead and develop the maximum inherent possibilities of oil circuit breakers.

As a result of this, I believe that the situation in this country is a particularly healthy one in that both of these developments, the air-blast and improvements in conventional oil circuit breakers, can go on in parallel without undue haste or pressure on either one. In this way, we are more likely to realize the maximum possibilities of each of these lines of developments.

When the Boulder Dam breakers were designed and built, a drastic step was taken in going from the standard eight-cycle breaker to the three-cycle breaker which that job required. This step was also a very costly one. I believe it is therefore a very sound and desirable procedure to develop a breaker which falls in between these two categories, namely, the five-cycle breaker, which apparently can be done with very little increase in cost over the present eight-cycle breaker. At the same time the gain in speed is a very substantial one and while its importance may not be fully apparent to all users at the present time, nevertheless we believe that it is certain to become more and more important as time goes on. On our own system, this increase in speed is already of considerable importance in connection with the application of ultrarapid reclosing of circuit breakers which has now passed beyond the pioneering stage and is taking its place as an important part of our system planning.

J. B. MacNeill: The field of switchgear may be divided into three principal parts as follows:

Low-voltage industrial

Medium-voltage powerhouse and substation

High-voltage transmission

The three papers presented as a group respectively by Ludwig and Grissinger (pages 414–20), Dickinson (pages 421–6), and MacNeill and Hill outline progress in each of these divisions.

The last-mentioned paper is timely in view of the discussion in engineering circles of the speeds which are necessary in high-power circuit breakers for modern system operation. The diversity of opinion on this subject seems remarkable until the variety of system operating conditions is fully considered. On some systems the present eight-cycle standard is more than adequate because of the solidity with which the system is tied together. There will be an increasing number of cases, however, where severe short circuits involving more than one phase wire will demand faster breaker operation than eight cycles. For such service five cycles seems a reasonable standard, as it can be obtained without marked increase in cost and with reliable equipment permitting numerous operations and providing high-speed reclosing.

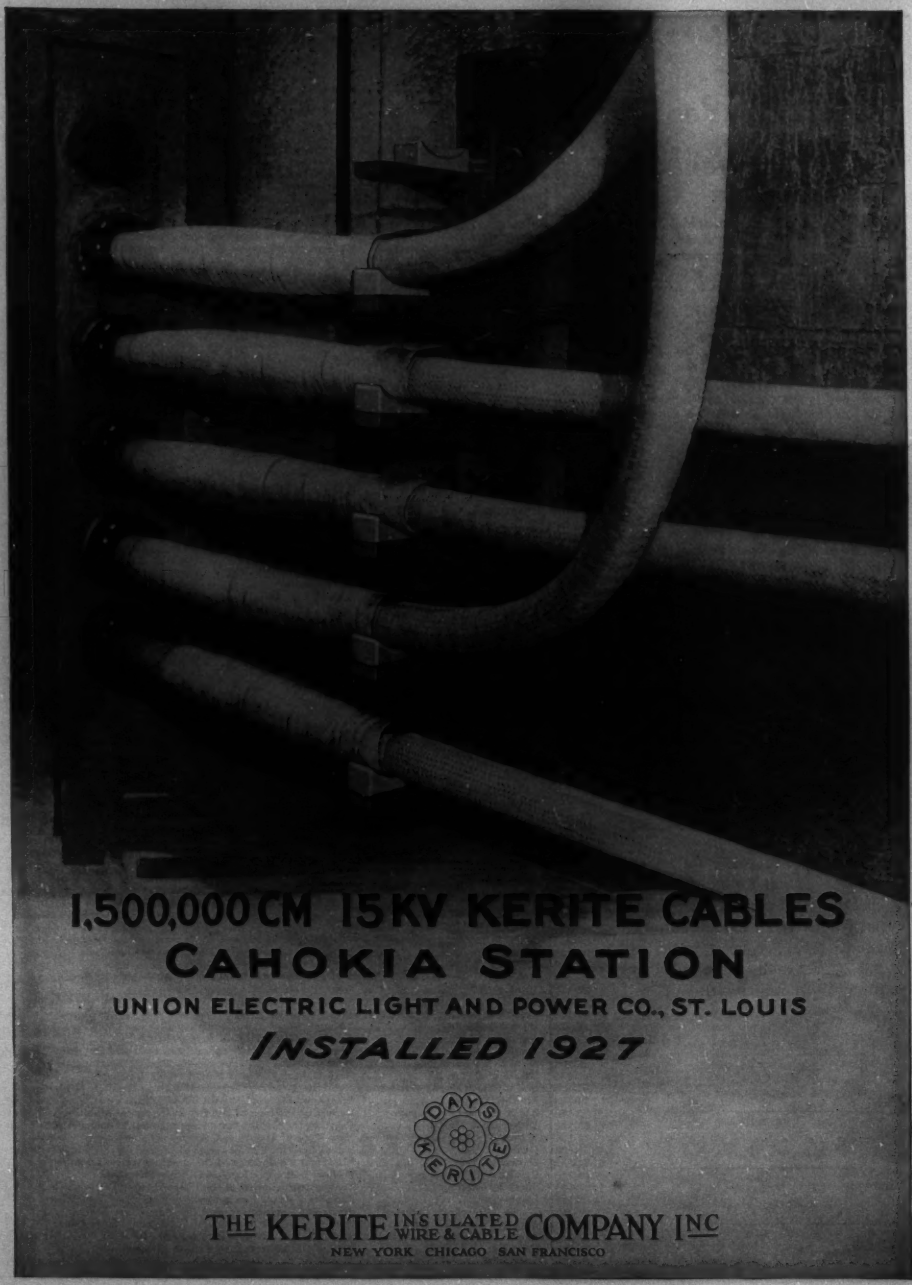
A feature of this paper is the data from cathode-ray oscillograph records taken simultaneously with the magnetic oscillograph records under various conditions of circuit opening from charging currents up to a dead short circuit of 2,250,000 kva direct on Laguna Bell bus of the Southern California Edison Company. These records are of particular interest in view of the discussions now before the Institute on possible rates and magnitudes of transient voltages during switching operations. The values of switching transient voltages given in this paper are reassuring to American operating people using grounded neutrals. We are assured that these values are consistent with the results given by Evans, Monteith, and Witzke and Van Sickle. An increased use of the cathode-ray oscillograph under fault conditions on operating systems is desirable as it is apparent that some data taken by magnetic oscillographs is not accurate for high-frequency transient phenomena.

Mr. Skeats has asked if there is a co-relation between the recovery voltage data in the MacNeill-Hill paper and the results in the Evans, Monteith, and Witzke paper. We are assured that the two sets of data are in harmony for similar system conditions, and from this we can conclude that the average American grounded-neutral high-voltage system is not subjected ordinarily to extremely high switching voltages and that the more severe voltage transients referred to in the Evans, Monteith, and Witzke paper occur only infrequently and under unusual system conditions. Mr. Prince infers that the De-ion grid shown in this paper is approaching an oil-blast design. Fundamentally the De-ion grid theory is observed in this design; that is, the arrangement of oil pools and splitter plates is essentially the same as on all De-ion grids and the iron is still present to accelerate the arc, particularly on low currents, and to drive it into the restricted slots where deionization is carried out. Grids of this type have been made with and without iron and we feel that the presence of iron improves the grid operation.

Mr. Gay and Mr. Sels of Public Service Electric and Gas Company state that five cycles is not usually necessary for high-voltage circuit breakers, and to this we agree. Public Service of New Jersey, however, is fortunate in having a compact high-power system without marked stability problems. High speed of opening operation, however, particularly when coupled with high speed of reclosure is definitely showing great improvement in stable operation in several outstanding cases. In one such case the stable limit of a 138-kv line was multiplied by three by the installation of circuit breakers which opened and reclosed in 24 cycles. The alternative in that case to such high-speed operation was a parallel line.

Mr. Lott has presented an interesting discussion of Southern California Edison and has pointed out the large number of heavy short circuits which have been handled during their test program without any considerable system difficulty. This in itself is a tribute to the higher speed of breaker operation generally found during the tests, as well as to the ruggedness of the Southern California system and the care with which the system was arranged for the tests.

Mr. St. Clair of the American Gas and Electric Service Corporation has commented on the improvement in modern circuit breakers, both in interrupting ability and in reclosure speeds without departing from the underlying features of standard designs. There are considerable advantages to incorporating these modern features of operation in structures which are known to be adequate for American operating conditions. The operators are thus able to secure equipment familiar to their people and also in many cases to incorporate the high-speed features in old equipment with consequent saving in station construction costs. The general use of grounded neutral systems in America demands more frequent circuit-breaker operation than is the case with ungrounded neutrals, and our first requirement must be the adequacy of the circuit breaker for high-power duty, possibly repeated several times without maintenance, and with a growing demand for instantaneous reclosure.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Papers Presented at South West District Meeting, Houston, Tex., April 17–19, 1939

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☐ 39-77	Doyle	The Mountain Creek Plant
☐ 39-78	Reynolds	Combined Voltage and Phase-Angle Control Under Load
☐ 39-79	Starbird & Mathis	Some Applications of the Type "J" Carrier System
☐ 39-80	Ilgenfritz, Hunter & Whitman	Line Problems in the 12-Channel Open-Wire Carrier System
☐ 39-81	Vaughan	Out-of-Step Blocking and Selective Tripping
☐ 39-82	Miner	Resonant-Type Constant-Current Regulators
☐ 39-83	Nash & Palmer	Electrical Equipment Used in Seismograph Prospecting
☐ 39-84	Evans	Electricity in an Oil-Field-Equipment Manufacturing Plant
☐ 39-85	Boehne & Weil	Equivalent Electrical and Mechanical Systems
☐ 39-86	Starr	Application of Factory-Built Substations
☐ 39-87	Kennedy & Bancker	Carrier Pilot Relaying
☐ 39-88	Peterson	Improvements in the Construction of Condenser Bushings
☐ 39-89	Reed	Mutual Inductance, etc., Expressed in Terms of Matrices
☐ 39-90	Browder	Signaling Over Zero-Sequence Network
☐ 39-91	Hanna, Oplinger & Valentine	Recent Developments in Generator Voltage Regulation

Papers Presented at North Eastern District Meeting, Springfield, Mass., May 3–5, 1939

☐ 39-92	Paus & Corson	A New Measuring Instrument for Direct Current
☐ 39-93	Laughlin, Pakala & Reagan	Carrier Losses and Interference on Boulder-Los Angeles Line
☐ 39-94	Patterson	Radio as a Means of Bridging Gaps in Telephone Lines
☐ 39-95	Hanna, Oplinger & Mikina	Recent Developments in Speed Regulation
☐ 39-96	Kimbark	Two-Phase Co-ordinates of a Three-Phase Circuit
☐ 39-97	Ross & Sterrett	Hydrogen-Cooled Turbine Generators
☐ 39-98	Hobson & Lewis	Regulating Transformers in Power-System Analysis
☐ 39-99	Bellaschi & Manning	Dielectric Strength of Porcelain
☐ 39-100	Clem	Equivalent Circuit Impedance of Regulating Transformers
☐ 39-101	Goodhue	The Rectifier Calculus
☐ 39-102	Richardson	Turbine-Electric Textile Range Drives
☐ 39-103	Untersee	Characteristics and Power Requirements of Spinning Frames
☐ 39-104	Graves	Electrical Equipment on Machine Tools
☐ 39-105	Snell	The Hydrogen-Cooled Turbine Generator
☐ 39-106	Mortensen & Ryan	Some Factors in the Design of High Speed Turbogenerators
☐ 39-107	Laffoon & Rose	Special Problems of Two-Pole Turbine Generators
☐ 39-108	Paine & Brown	Corona Discharge on Rubber-Insulated Cables
☐ 39-109	Dawes & Humphries	Characteristics of Restricted Ionization
☐ 39-110	Seaman	Modern Trends of Low-Voltage Air Circuit Breakers

Papers Presented at Summer Convention, San Francisco, Calif., June 26–30, 1939

☐ 39-93	Laughlin, Pakala & Reagan	Carrier Losses and Interference on Boulder-Los Angeles Lines
☐ 39-97	Ross & Sterrett	Hydrogen-Cooled Turbine Generators
☐ 39-105	Snell	The Hydrogen-Cooled Turbine Generator
☐ 39-106	Mortensen & Ryan	Some Factors in the Design of High-Speed Turbogenerators
☐ 39-107	Laffoon & Rose	Special Problems of Two-Pole Turbine Generators
☐ 39-111	Whitehead	The Dielectric Strength and the Life of Impregnated Paper
☐ 39-112	Race	Dielectric Strength of Insulating Liquids
☐ 39-113	Race	Tests on Oil Impregnated Paper—IV
☐ 39-114	Holtz	Behavior of Single-Phase A-C Watt-hour Meters at No Load
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☐ 39-136	Dickerson & Mahan	Painting the Golden Gate International Exposition with Light
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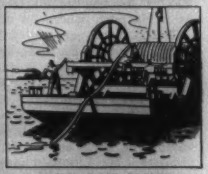

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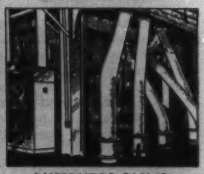

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Industrial Notes

Appointments and Promotions.—G. S. Crane has been appointed vice-president in charge of sales and engineering of Cutler-Hammer, Inc., Milwaukee. He was formerly head of the sales division. B. M. Horter is now general sales manager. He has been associated with the company since 1921. . . . Guy W. Wilson has been made manager of the General Electric's transportation department. He succeeds E. P. Waller, who is now assistant to E. O. Shreve, vice-president in charge of apparatus sales. . . . . After nearly 40 years devoted to wire and cable activities, W. H. C. Smith has retired from the General Electric construction materials sales division at Bridgeport, where he was assistant to J. H. Crawford, manager of the division. . . . W. O. Lippman has been appointed works manager of the East Springfield, (Mass.) Works of the Westinghouse Electric & Mfg. Co. Products manufactured in this plant include household refrigerator units, air conditioning and commercial refrigeration equipment, water coolers, fans and vacuum cleaners. Mr. Lippman has been associated with the company for the past 16 years.

G-E Sales and Merger.—Orders received by the General Electric Co. during the first six months this year amounted to $169,071,646 compared with $128,223,823 for the same period last year, an increase of 32 per cent. . . . The General Electric Vapor Lamp Co., Hoboken, N. J., has been merged with the incandescent lamp department of General Electric Co. Because of this change, effective July 1, by which activities in incandescent and electric discharge lamps are brought together, the incandescent lamp department will hereafter be known as the lamp department of the General Electric Co., according to a recent announcement.

Trade Literature

Circuit Breaker Panelboards.—Bulletin 58, 16 pp. Describes a-c circuit breaker panelboards and cabinets. Frank Adam Electric Co., St. Louis, Mo.

Lighting Units.—Bulletin, 8 pp. Describes new illumination units, steel standards and brackets for street illumination. The Daunt Corp., 110 E. 42nd St., New York, N. Y.

Radio Transmitter Capacitors.—Catalog 160-T, 36 pp. Lists and describes 13 types of capacitors designed for use in the broadcast and industrial fields. Cornell-Dubilier Electric Corp., South Plainfield, N. J.

Noise Meters.—Bulletin, 8 pp. Describes portable, direct reading microvoltmeter for measuring all types of radio noise and carrier fields. Ferris Instrument Corp., Boonton, N. J.

Transformers.—Bulletin B6000, 16 pp., "Portfolio of Unusual Power Transformers." Illustrates installations of large capacity power transformers of various types. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Bridge for Temperature Measurement.—Catalog E-33C(1), 16 pp. Describes a new Mueller resistance thermometer bridge for highly precise measurements of temperatures from absolute zero to 500° C. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

Voltage Regulators.—Bulletin GEA-1577E, 20 pp. Describes three-phase step voltage regulators for 4,800- to 66,000-volt circuits. The range of regulation provided is from 10 per cent raise to 10 per cent lower, in 16 or 32 equal steps. General Electric Co., Schenectady, N. Y.

Lightning Arresters.—Cat. 404, 112 pp. A comprehensive treatment of lightning protection for distribution systems and equipment. Describes various types of Crystal Valve lightning arresters and applications to apparatus and lines. Electric Service Supplies Co., 17th & Cambria Sts., Philadelphia, Pa.

Magnet Wire.—Catalog C-352, 92 pp., Describes all types of magnet wire and magnet wire coils. Includes valuable technical data and wire tables, specifications, etc. A small size pocket handbook (40 pp.) is also available; contains comprehensive technical tables useful to the engineer and shopman. Anaconda Wire & Cable Co., 25 Broadway, New York, N. Y.

Lightning Protection Devices.—Bulletin 680-H, 8 pp., "Lightning Protection at Lightning Speed with O-B Control Gaps." Discusses the problem of protecting stations from lightning, explains operation of O-B control gaps and where they may be installed to best advantage. Ohio Brass Co., Mansfield, O.

D-C Switchboards.—Des. Data. 31-132, 12 pp. Describes small-capacity switchboard panels for the control of generators and feeders used for general power and lighting service in small d-c plants. The maximum generator ratings covered are 75 kw, 125 volts, or 150 kw at 250 volts, with a maximum feeder rating of 600 amperes. Westinghouse Electric & Mfg Co., East Pittsburgh, Pa.

Demand Meters.—Bulletin GEA-3133, 8 pp. Demand Limiting Meters. . . . . Bulletin GEA-3121, 8 pp., Indicating A-C Demand Meters. . . . . Bulletin GEA-3123, 12 pp., Graphic A-C or D-C Round Chart Meters. . . . . Bulletin GEA-3125, 12 pp., Printing Demand Meters. . . . . Bulletin GEA-3130, 16 pp., Contact Devices for Watthour Meters. . . . . General Electric Co., Schenectady, N. Y.

Nickel and Alloys.—Bulletin, 16 pp., "Tremendous Trifles." Presents technical and mechanical data on nickel, Monel, Inconel, "Z" Nickel, "K" Monel, and other high nickel alloys as used for such parts under service conditions where ordinary materials might fail. Some electrical applications are illustrated. The International Nickel Co., Inc., 67 Wall St., New York, N. Y.

Circuit Breakers.—Bulletin 536, "A Method of Interlocking Enclosed Thermal Circuit Breakers." In addition to the interlock mentioned in the title, the bulletin describes a new feeder circuit breaker, structure of truck-type circuit breakers, completely enclosed transfer switches, the 23-kv bus at Boulder Dam, an interlock for power auxiliary breakers, etc. I-T-E Circuit Breaker Co., 19th & Hamilton Sts., Philadelphia, Pa.

Rectifiers.—Bulletin TC-51, 12 pp. Describes Balkite "taper" rectifiers and d-c power units for telephone, utility, and industrial signal service. This taper charge system is based upon an inherent property of the tantalum rectifier which, when used with a transformer of the proper type, automatically raises and lowers the charge in direct proportion to the load demand on the battery. The rectifying Elements do not age and lose output with use, and are not affected by severe changes in temperature. Prices are listed. Fansteel Metallurgical Corp., North Chicago, Ill.

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New Products

Polystyrene Insulating Film.—Developed for electrical insulation purposes by the Bakelite Corporation, 247 Park Ave., New York City, Bakelite polystyrene film is said

to possess the many advantages found in Bakelite polystyrene molding material. The new film is applicable particularly in wound capacitors for radio sets and other types of electrical equipment. The electrical properties of the film will remain constant even at varying temperatures, an important consideration in the manufacture of capacitors, which require stable capacitance not only with changes in temperature but also for various frequencies. The film is water white in appearance but may be had also in a tinted shade of purplish black. It is supplied in ribbons $1^1/_2$ and $2^1/_2$ inches wide. The standard thickness is 1 mil.

Thermal Converter.—A new thermal converter, known as the "Thermoverter," makes it possible to measure a-c electric power with any potentiometer or D'Arsonval

millivoltmeter. According to the manufacturer, the Bristol Company, Waterbury, Conn., this device can be used with either a direct-deflecting millivoltmeter or a potentiometer for measuring a-c power in an individual circuit; for totalizing the a-c power in a number of circuits; and for telemetering a-c power or totalized load. The Thermoverter, when connected in an a-c metering circuit (secondaries of a conventional set of instrument transformers) performs a proportional conversion from a-c watts to d-c millivolts. With it, a power load may be directly expressed by a d-c potential difference suited to transmission over considerable distance and for totalization. As there are no moving parts, operating attention is eliminated. The time of response between a change of a-c power load and the development of a proportional emf in the Thermoverter is less than $^1/_2$ second.

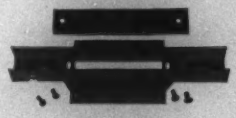
Paper-Wound Replacements For Electrolytics.—To meet the occasional demand for paper-wound replacements for metal-can and cardboard-case dry electrolytics, two new condensers have been developed by the Aerovox Corporation, New Bedford. Mass. The PWC series, matching in size and shape the dry electrolytic metal-can condensers, is available in three types replacing the 4-600, 8-600 and 8-8-600 electrolytics, with actual

capacities of 2.0, 2.75, and 1.75–1.75 mfd., respectively. The PWP series matches the cardboard-case dry electrolytics of 4-600, 8-600 and 8-8-600, with actual capacities of 2.0, 3.0, and 2.75–2.75 mfd. These paper replacement units have extremely low power factor and leakage. No polarity need be observed.

Guy Wire Guard.—A new development in guy wire guards, manufactured by the S. E. Overton Company, South Haven, Mich., and known as "Flexibal" guy guards,

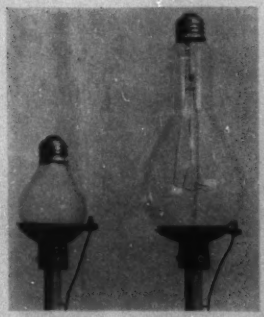
consists of a series of bead-like spindles, strung together to the required height. The spindles are made of hardwood, of rounded contour, slotted to permit placing on the wire, and aluminum-painted for high visibility. Each spindle has two nails inserted in drilled holes and their are 14 spindles to the set, providing a 7-foot guard. For installation, the only tool required is a hammer. The spindles are locked at the top by means of a rust resisting bolt clamp.

Junction Box.—A new junction box for feeding "plug-in" strip with any type of wiring material, has been placed on the



market by the National Electric Products Corporation, Fulton Building, Pittsburgh, Pa. The new box fits on any type of standard switch box or cover, roughed into place in advance, and provides adjustment to assure proper alignment with the "plug-in" strip. The box is made for the three types of "plug-in" strip—concealed flush (illustrated); baseboard cap, and chair rail.

Lamp Changer.—A new type of safety tool in the form of a suction cup lamp changer has been announced by the Suction Cup Lamp Changer Co., 826 Delaware St., Scranton, Pa. The device consists of an especially designed, pole-mounted, rubber suction cup. A string releases the suction

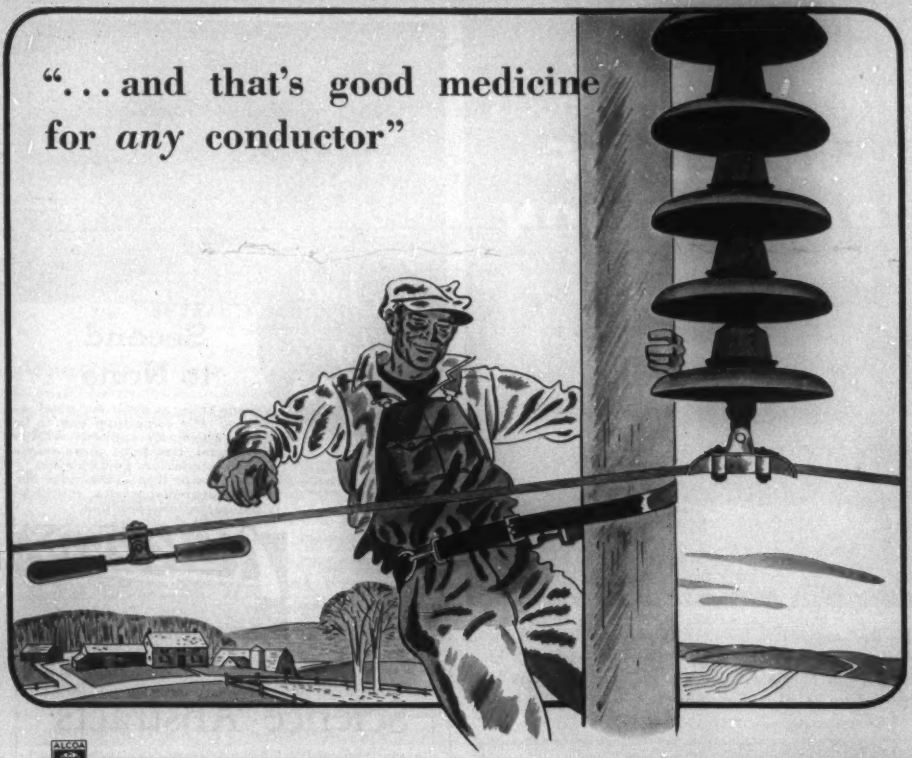


grip of the cup after a new lamp has been placed in the socket. The standard cup will serve for removing and replacing many different sizes of lamps, and is equipped with a 4-foot pole, to which extensions may easily be added.

For latest list of available pamphlet copies of AIEE papers, see page 6, advertising section.

All AIEE Standards are listed on page 14.

"... and that's good medicine for *any* conductor"



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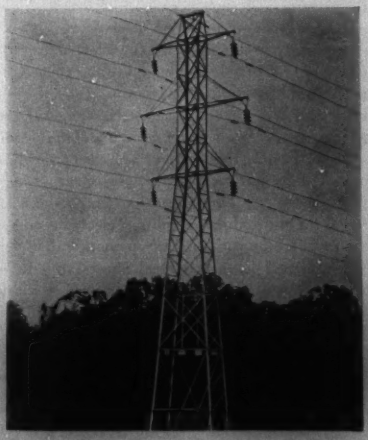

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When American Cystoscope Makers, Inc. planned this new model, they selected Bakelite Molded because it is light in weight, readily molded into any desired shape, high in dielectric strength, and impact-resistant. When the job was placed in production, other important advantages were gained as well. For example, assembly time is halved through elimination of hand operations, and through introduction of mechanical shortcuts such as the use of jigs, dies and fittings.

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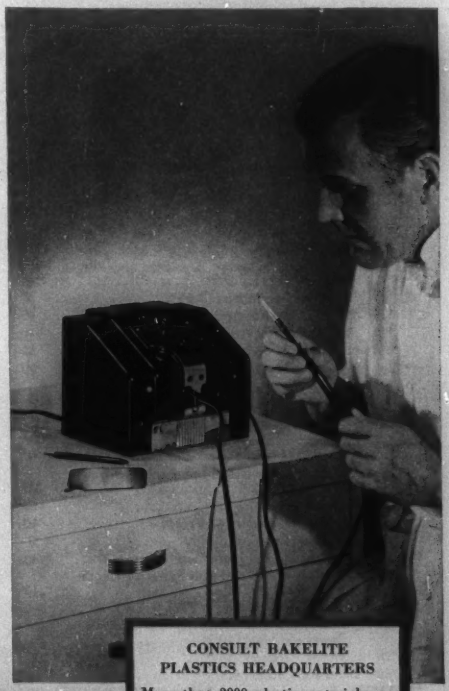

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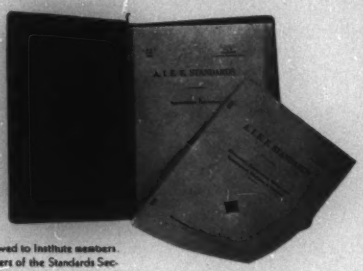

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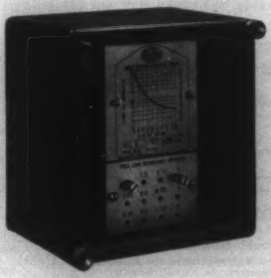

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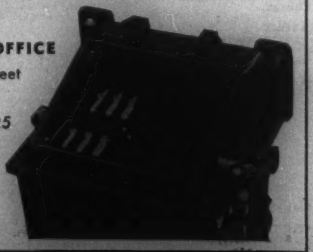

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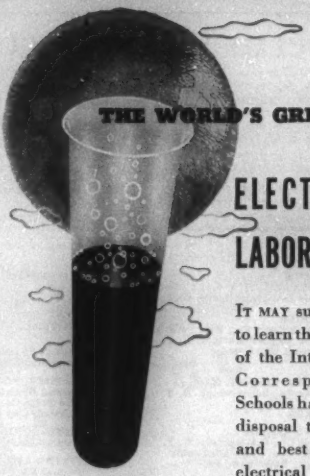

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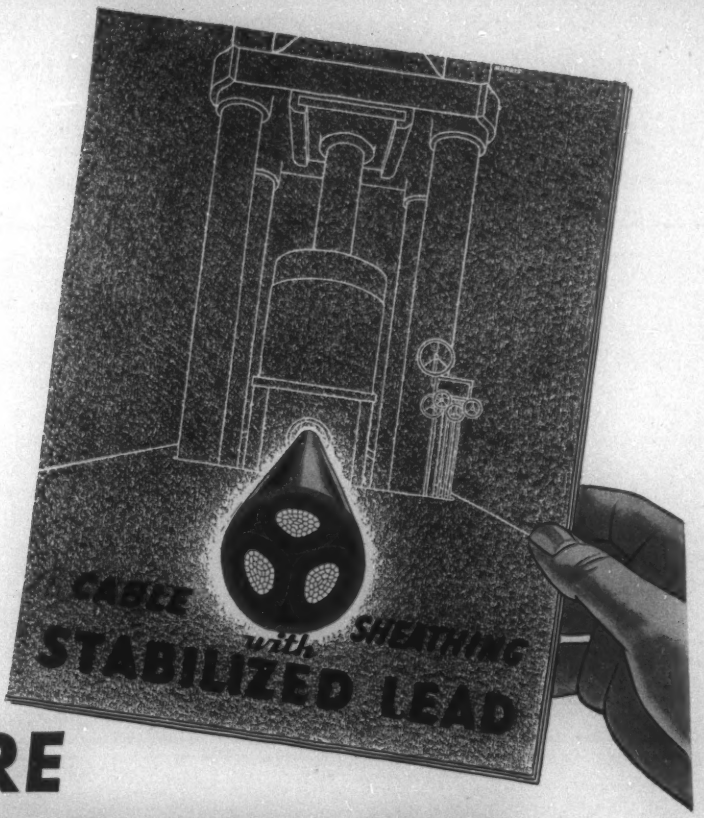

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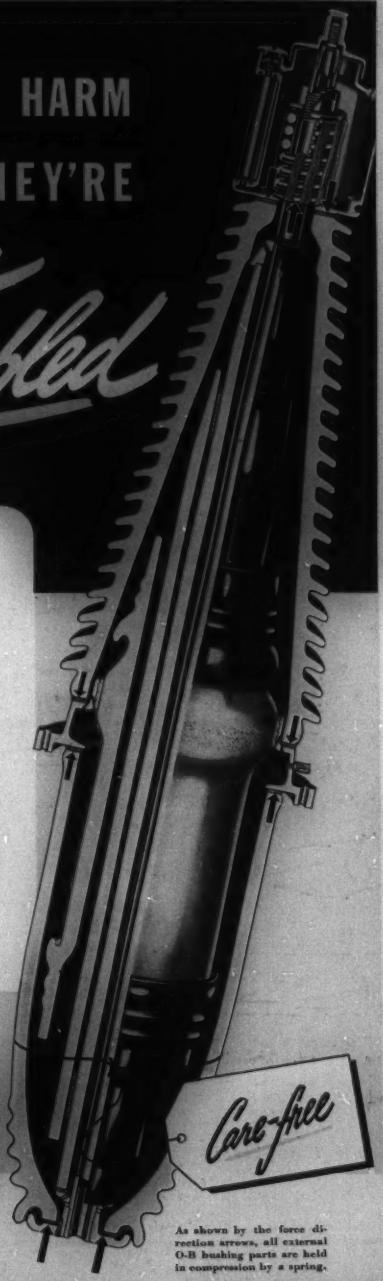

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